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Key words – Miocene, Marañon basin, Peru, Pebas Formation, Chambira Formation, stratigraphy.
This study of the type and scales of depositional processes and landscape development in western Amazonia during the Miocene is based on the description and interpretation of three boreholes from the Marañon basin (Peru). The Miocene Pebas Formation, and the overlying Marañon Formation and underlying Chambira Formation are lithologically characterised. An age calculation model indicates an Oligocene age for the Chambira Formation, and an Early – early Late Miocene age for the Pebas Formation. The base of the Chambira Formation is placed at a sequence boundary and corresponds to the beginning of a regression. The succession was deposited in floodplains included in a RST and a LST under a seasonal climate with a pronounced dry season. The base of the Pebas Formation is placed at a TS. It represents TST and HST lacustrine and swamp settings at or near sealevel, formed in a tropical monsoon climate alike the present-day climate in the region. At the time, the area was a mosaic of lakes, swamps and fluvial belts, but experienced tidal influence as well. During apparently regularly recurring base level highstands, open aquatic settings (lakes at sea level) were widespread. The depositional system was driven by tectonic subsidence in the area, uplift and erosion in the Andean hinterland and the western rim of the Pebas system (the developing Subandean zone), delta lobe switching and river belt avulsions, as well as presumable Milankovitch scale precipitation/erosion cycles and eustatic sea level variation. The base of the Marañon Formation is placed at a sequence boundary. It represents the end of the Pebas lake/wetland system, and the change to permanent fluvial conditions during the Late Miocene RST and LST.

Contents

Introduction 323
Material & methods 325
Lithological description of the wells 331
Correlation between wells 341
Age calculations and stratigraphic model 346
Discussion 346
Acknowledgements 353
References 353
Appendix 356

Introduction

Considerable debate exists over the type and scale of depositional processes in lowland western Amazonia during the Miocene. There is agreement over the dominance of large-scale aquatic settings at sea level during the late Early to early Late Miocene in the region, known as the Pebas lake/wetland system (Hoorn *et al*., 1995; Räsänen *et al*., 1996; Lundberg *et al*., 1998; Gingras *et al*., 2002; Wesselingh *et al*., 2002, 2006a, b). However, relatively little is known about the type of processes that shaped the region, and the structure and scale of the dominating aquatic landscapes during the Miocene. In other words, was the area predominantly occupied by a single or few very large lakes/embayments or was it predominantly a mosaic of smaller lakes, rivers and swamps alike the modern Pantanal at the Brazilian-Bolivian boundary? During the Miocene, western Amazonia was influenced by the tectonics of the nearby Andes, resulting in foreland basin subsidence variation, forebulge uplift and relocation, and thrust-sheet propagation, as well as sediment input from the west (Hermoza, 2005). The depositional settings in the Pebas system might have been entirely controlled by processes such as subsidence, river avulsion and delta lobe switching. In the past, eustacy (Hoorn, 1993; Hoorn *et al*., 1995; Räsänen *et al*., 1996; Hoviskoski *et al*., 2005) has also been indicated to play a role in the

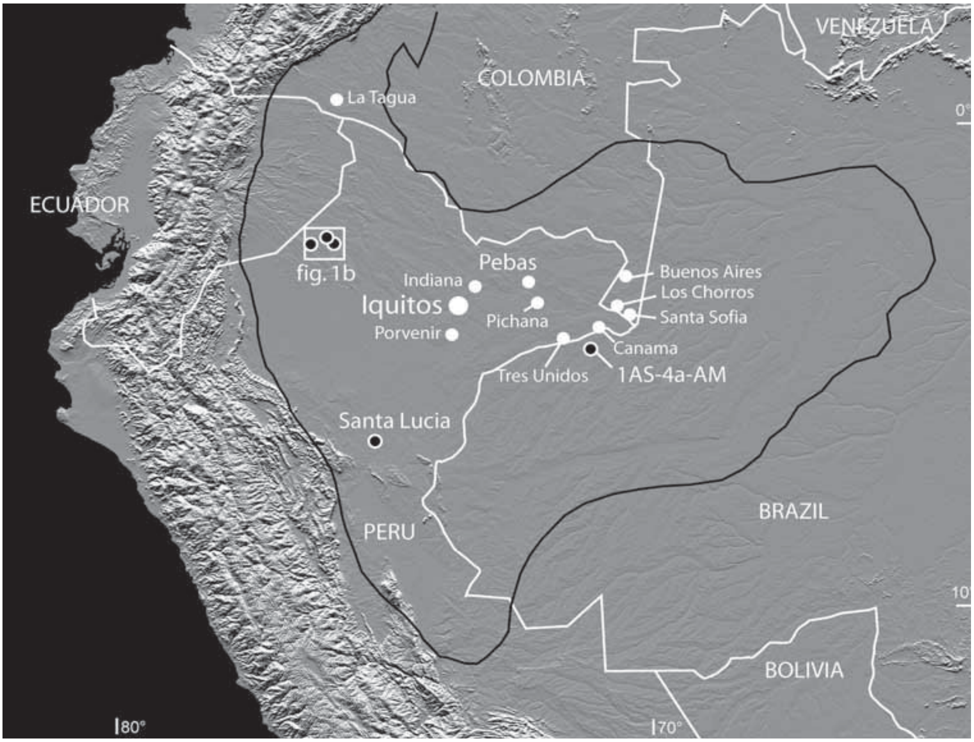


Fig. 1a. Location of the study area and localities mentioned in text. Black line depicts the approximate maximum limit of the Pebas Formation and associated deposits. Well 1AS-4a-AM was published in Hoorn (1993) and well Santa Lucia in Hermoza (2005). Background modified from www.photojournal.jpl.nasa.gov.

development of western Amazonia. The Pebas Formation, a Miocene fossiliferous unit present over a large area of western Amazonia, contains common, regularly developed transgressive-regressive sequences (Räsänen *et al*., 1998; Vonhof *et al*., 2003; Wesselingh *et al*., 2006b) that suggest more regular driving factors than autocyclic or non-cyclic processes. High levels of interconnectivity of aquatic landscapes are suggested by the presence of tidal deposits, alleged brackish ichnofossil assemblages and endemic mollusc species in single biozones (Wesselingh *et al.*, 2006a, b). Such interconnectivity may represent a large, single water body (lake or marginal marine embayment) or common occurrence of connection during periods of relative high base levels in the system. There is an apparent contrast with interpretations from the strontium-isotope record (Vonhof *et al.*, 2003), as well as borehole assessments made on Brazilian wells (Vonhof & Räsänen, unpublished data), that point to a mosaic depositional system with little interconnectivity. Outcrop series in the Pebas Formation usually cover no more than 30 m of stratigraphic thickness and can be laterally traced over 5 to 10 km at the best, therefore providing little information as to the size and (temporal and lateral) scale of the depositional system. Furthermore, the Pebas Formation is not formally defined, and relationships with the underlying Chambira Formation and overlying Marañon Formation have not been established hitherto. In this paper we use wells from the Peruvian Marañon (foreland) basin to study the stratigraphy of the Pebas Formation, including its relationship with the Chambira and Marañon formations. We investigate the amount of lateral continuity of layers and depositional environments within the Pebas Formation and assess the role of different processes (internal and external) that shaped the system.

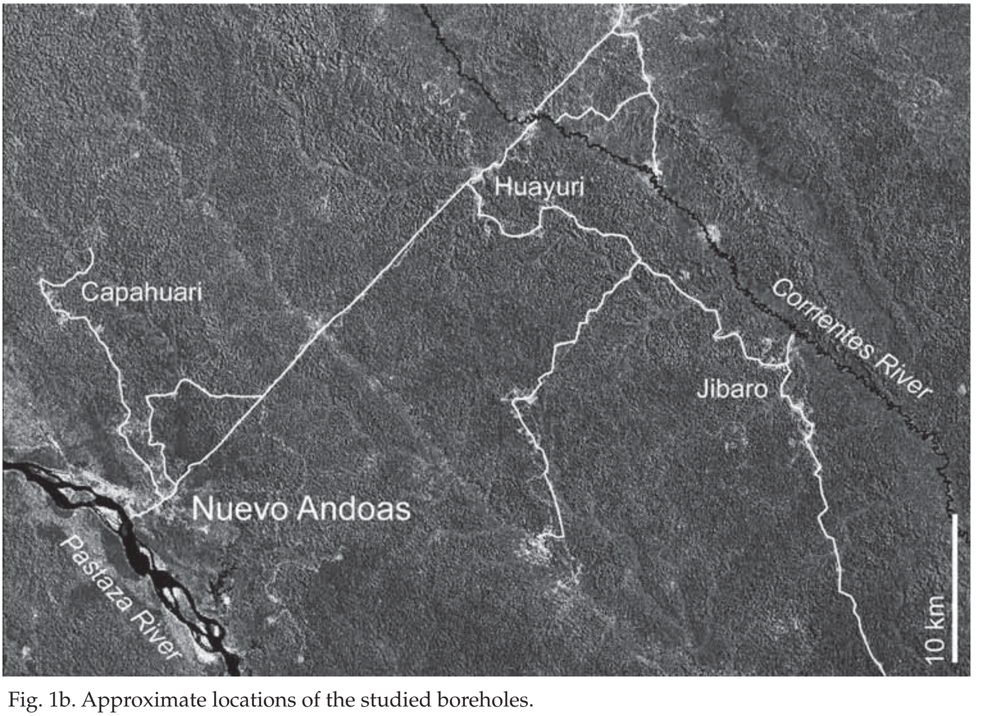


Fig. 1b. Approximate locations of the studied boreholes.

Recently, great advances have been made in the understanding of the structure, stratigraphy and regional depositional processes acting during the Miocene in the Peruvian Subandean zone and the foreland basins (Hermoza, 2005; Hermoza *et al.*, 2005). For the Marañon basin, the insights lean heavily on interpretations of well logs and seismic profiles (Hermoza, 2005), but a lithological definition for the Pebas Formation, and a detailed assessment of upper, lower and lateral boundaries, is still lacking. In this paper we follow the stratigraphic terminology for the Subandean zone and the Marañon basin as used by Hermoza *et al.* (2005) and Hermoza (2005), but our lithostratigraphic approach does result in slightly different boundaries. Based on the new well data, we make suggestions for the lithological definition of the Pebas Formation.

Material & methods

Three wells (Capahuari, Huayuri and Jibaro) from Occidental Petrol de Peru S.A. from the Loreto department in Peru were studied. The wells were drilled in the 1990s in the Pastaza-Marañon basin, between the Corrientes and Pastaza Rivers near the border with Ecuador (Fig. 1). Well logs and small cutting samples (taken at 50 ft intervals) from alleged Pebas Formation deposits were studied. At the onset of the study, the upper and lower boundaries of Pebas Formation were uncertain, and we therefore included intervals containing the underlying Chambira Formation and overlying Marañon Formations. The well logs of the three studied wells were compiled by F. Garcia-Zabaleta (Occidental Petrol de Peru). Depths are indicated in feet, unless stated otherwise.

Capahuari – Capahuari Norte 9 (1AB-3-204). 28/3/1996-21/5/1996. Plane coordinates: N = 1′793,309.4 m.; E = 664,680.5 m. Elevation: Ground level (GL) 260.0 m. 853′; Kelly Bushing (KB) 269.7 m. 885′. Depth of borehole: 12120 ft. Samples studied from interval 2000-5050 ft. Studied parameters; spontaneous potential (SP), gamma ray (GR), intermediate resistivity (SFLU; spherical focused log) and deep resistivity (ILD: induction log deep).

Huayuri – Huayuri Sur 15 (1-AB-15-184D). 5/10/1992-30/11/1992. Plane coordinates: N = 1′799,620.13 m.; E = 694,394.56 m. Elevation: GL 269 m. 790′; KB 269 m. 814′. Depth of borehole: 11130 ft. Samples studied from interval 2000-5450 ft. Studied parameters; spontaneous potential (SP), gamma ray (GR), intermediate resistivity (SFLU), deep resistivity (ILD) and sonic interval travel time (DT).

Table 1. Crude mollusc biozonation scheme. CZ refers to Crude Zone.

Mollusc species	CZ1	CZ2	CZ3	CZ4
Dyris denticulatus Wesselingh	X			
Dyris lataguensis Wesselingh	X			
Cochliopina? *colombiana* Nuttall	X			
Charadreon eucosmius (Pilsbry & Olsson)	X	X		
Sheppardiconcha colombiana (Nuttall)	X			
Sheppardiconcha lataguensis Nuttall	X			
Sheppardiconcha tuberculifera (Conrad)	X	X	X	
Pachydon obliquus Gabb		X	X	X
Pachydon cebada (Anderson)	X			
Pachydon hettneri (Anderson)	X			

Jibaro – Jibaro 7 (1AB-21-181). 29/5/1992-22/7/1992. Plane coordinates: N = 1'789,578.50 m.; E = 715,798.53 m. Elevation: GL 209.45 m. 687'; KB 216.77 m. 711'. Depth of borehole: 9720 ft. Samples studied from interval 1000-4450 ft. Studied parameters; spontaneous potential (SP), gamma ray (GR), intermediate resistivity (RSN: resistivity short normal), deep resistivity (ILD) and sonic interval travel time (DT).

Rock samples from the Pebas Formation are in general poorly consolidated and often disintegrate easily when washed. The samples, taken at 50 ft intervals, were analyzed for mollusc species. In Wesselingh *et al.* (2006a), a mollusc biozonation for the Pebas Formation has been erected from outcrop work and this zonation is applied to the well samples. The samples yielded few molluscs. In deeper sections the admixture of very different preservation styles and species only known from 'young' stratigraphic intervals points to common contamination (downfall, also known as caving). Such fragments have been indicated during analyses. The amount of contamination in the samples is such that only Last Occurrence Dates (LOD) could be used as reliable stratigraphic data. The poor yield only allowed the use of some common species in stratigraphic analysis. As a result, only a crude mollusc zonation was established, with four mollusc zones indicated as Crude Zones (CZ: Table 1, first mention (see remark last page) Fig. 2). We have refrained from formally naming these zones in order to avoid confusion with the more refined mollusc zonation (MZ) of Wesselingh *et al.* (2006a).

CZ1 coincides with part of the Early Miocene *Psiladiporites-Crototricolpites* concurrent range zone of Hoorn (1993) and to older Early Miocene palynomorph zones as well. Deposits referred to as La Tagua Beds (= lowermost Pebas Formation of Wesselingh *et al.*, 2002) are also included in the CZ1. The top of the CZ1 is defined by the last occurrence of *Dyris denticulatus* and/or *Dyris lataguensis*. CZ2 coincides with the upper part of Hoorn's (1993) *Psiladiporites-Crototricolpites* concurrent range zone that is approximately late Early to early Middle Miocene (latest Burdigalian-Langhian) and the base of her *Crassoretitriletes* interval zone (Middle Miocene). Outcrops attributed to the former zone in Peruvian Amazonia include Santa Teresa and Indiana (Hoorn, 1994; Fig. 2). The top of the CZ2 is defined by the last occurrence of *Charadreon eucosmius*. CZ3 covers most of Hoorn's *Crassoretitriletes* interval zone. The age of CZ3 is Middle Miocene. Outcrops attributed to this zone include Iquitos, Pebas and Santa Rosa de Pichana (Hoorn, 1994; Wesselingh *et al*., 2006b; Fig. 2). The top of this zone is defined by the LOD of *Sheppardiconcha tuberculifera*. CZ4 corresponds to Hoorn's *Grimsdalea* interval zone and is late Middle to early Late Miocene (Late Serravallian-Early Tortonian). The Colombian outcrops of Los Chorros (Hoorn, 1994), Buenos Aires (Vonhof *et al.,* 1998) and Santa Sofia (Wesselingh *et al.,* 2006a), and the Peruvian outcrops Canama, Tres Unidos (Nuttall, 1990) and Porvenir (Räsänen *et al.,* 1998), fall within this zone (Fig. 2). The zonation applied to wells is crude, reflecting low numbers of fossils recovered from the studied samples. The CZ boundaries are, therefore, subject of some uncertainty (typically of 50-150 ft).

The available wire line logs and lithological descriptions presented on the well logs, as well as the cutting samples were used to describe lithologies, and to indicate and assess boundaries between geological units. We subdivided the succession into formations and informal subunits, following the recommendations outlined in the stratigraphic guide of the International Commission on Stratigraphy (Salvador & Hedberg, 1994). The attribution of intervals to formations follows as closely as possible lithological criteria and formation names used by Hermoza (2005), reflecting the nomenclature

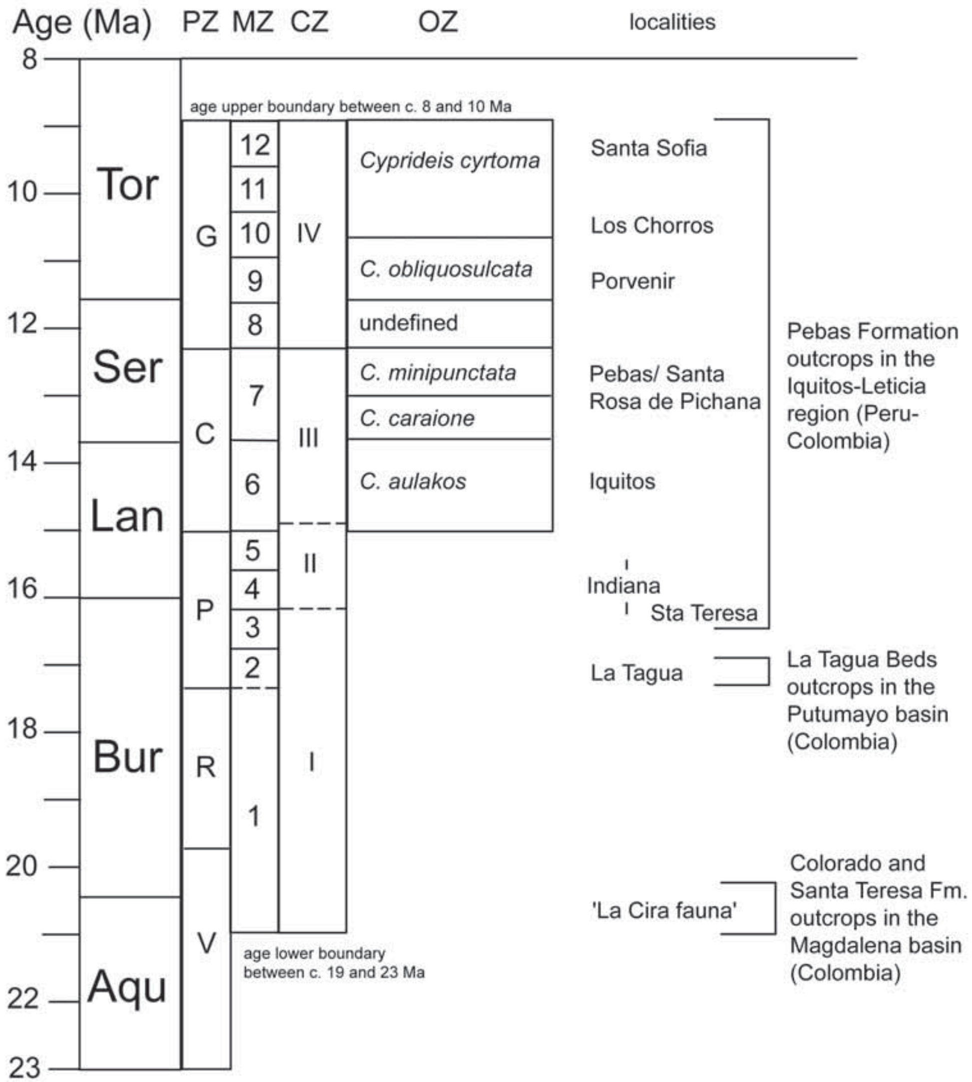


Fig. 2. Stratigraphic framework. Key: PZ = palynology zone (Hoorn, 1993); V = *Verrutricolporites* Zone; R = *Retitricolpites* Zone; P = *Psiladiporites-Crototricolpites* Zone; C = *Crassoretitriletes* Zone; G = *Grimsdalea* Zone; MZ = molluscan zone (from Wesselingh *et al.*, 2006a); CZ = crude molluscan zone; OZ = ostracod zone; Aqu = Aquitanian; Bur = Burdigalian; Lan = Langhian; Ser = Serravallian; Tor = Tortonian. Note that ages of the upper and lower boundaries of the Pebas Formation are uncertain.

used by PetroPeru. We deviated, however, in one case. At the base of the Chambira Formation we found a thin (30-124 ft/ 9-38 m) interval characterised by a well-expressed alternation of sandstone and mudstone intervals. We found this basal interval to be very useful and established three subunits for the Chambira Formation instead of the two used by Hermoza (2005). At the moment of writing of this paper, a separate initiative (under the Proyecto Diversidad Biológica de la Amazonía Peruana (Biodamaz) programme of the Instituto de Investigaciones de la Amazonía Peruana (IIAP) and the University of Turku) is working to standardize stratigraphic definitions of units found in the Peruvian Amazon region. Therefore, we have refrained from formally naming subunits ourselves. After the lithological descriptions and the subdivision of the wells into geological units, the mollusc biozone boundaries and the boundary between the Pozo Formation and Chambira Formation were used as a starting point for correlation.

Glauconite has been indicated on the well logs from several of the studied intervals. Glauconite is an authigenic mineral that is formed in tropical marine conditions, especially in the outer margins of continental shelves in areas with low sediment input (Stonecipher, 1997). Such depositional environments are difficult to envisage during the Miocene in western Amazonia. However, the mineral and its oxidizing products are easily reworked, and can have been washed in with rivers draining marine Mesozoic and Paleogene sandstones in the nearby Andes. Glauconite may also form as an authigenic mineral during early diagenesis in, for example, floodplains. Similar greenish minerals, such as chlorite (that we encountered on some of the outcrop samples studied), may also be present in such fluvial suites and may have been confused with glauconite. Whenever the lithology log of the boreholes mentions the presence of glauconite, we have used the term 'green minerals' instead.

Markerbed correlation (Kent, 1992) was attempted using sandstones, coals, mudstones/claystones and shell beds. Sandstone intervals were interpreted by a combination of the SP showing negative excursions from the shale baseline, a simultaneous negative excursion of the GR and a positive excursion of resistivity curves. In various cases such a combination corresponded to a shell carbonate on the lithology log, described on the well log as shell beds with siltstone or sandstone matrix. Shell beds with sandstone matrix are common in outcrops and they have been here included in the analyses of sandstone layers. Coals may provide marker beds in continental settings (Nichols & Uttamo, 2005) and several such layers outcrop laterally over several kilometres. However, the lateral variability of coals seen in the field and their general thin nature (typically decimetre scale, that is, below the general resolution of the lithology descriptions of the wells) makes them poor correlation marker beds for the Peruvian wells. In marine systems shell beds can be used as correlation marker beds. Transgressive shell beds provide (in the scale of the present study) near isochronous marker horizons. Although potential transgressive shell marker beds have been encountered regularly in studied outcrops (Gingras *et al*., 2002), the thickness of these (typically below 1 m) should fall below the resolution of the well data. On the other hand, some of the shell beds attributed to sandstone layers (see before) might represent either transgressive or regressive shell beds. In marine systems, highstand shell beds may develop as a result of sediment starvation, resulting in strongly time-averaged, hardground type shell beds that can be enriched in diagenetic phosphate. Such shell beds have not been seen in the field or in the well data and samples.

Sequence stratigraphy terminology follows the modifications proposed by Guerrero (2002) to the original Exxon terminology (e.g., Posamentier *et al*., 1988; Posamentier & Vail, 1988; van Wagoner *et al*., 1990). According to Guerrero (2002), the systems tracts are recognized by their predominant trends in sedimentary patterns. Relative base level instead of eustatic sea level change is considered to control the sedimentary patterns.

Relative base level results from interaction of global sea level with variable rates of sediment input and basin subsidence. A systems tract contains only a single sedimentary pattern, either progradational, retrogradational or aggradational. Strata deposited during relative base level fall are included in the Regressive Systems Tract (RST) and identified by a succession of shallowing-upward environments indicated by coarsening-upward facies in a progradational pattern. Strata deposited during lowest sea/lake or base level are included in the Lowstand Systems Tract (LST) and identified by an aggradational interval in which relative low base level is maintained and dominant sedimentary environment does not change. Strata deposited during relative base level rise are included in the Transgressive Systems Tract (TST) and identified by a succession of deepening-upward environments indicated by fining-upward facies in a retrogradational pattern. Strata deposited during highest base level are included in the Highstand Systems Tract (HST) that are identified by an interval with aggradational pattern in which relative high base level is maintained and dominant sedimentary environment does not change. The Sequence Boundary (SB) coincides with the Regressive Surface (RS) placed at the base of the RST. The Lowstand Surface (LS) is placed at the base of the LST. The Transgressive Surface (TS) is placed at the base of the TST. The Maximum Flooding Surface (MFS) is placed at the base of the HST. The Pebas Formation included in this study in a TST and a HST which lasted 12-14 Ma, and could in turn be subdivided in short-term transgressive-regressive (T-R) sequences (estimated to represent tenths of thousands of years) including mainly TST and RST, but also with some well developed HST and LSTs.

In order to assess the continuity of depositional environments within the Pebas Formation, we considered the occurrence of transgressive and maximum flooding surfaces associated with short-term TSTs and HSTs that might form regional, up to basin-wide, isochronous marker horizons. Mudstones or claystones deposited on TSs were interpreted based on their position above coarsening-upward sandstones, a combination of positive GR excursions and negative resistivity excursions (Asquith, 1982), and additional information from the lithology logs and rock samples. From recent outcrop observations and published studies of the Pebas Formation (Räsänen *et al*., 1998; Gingras *et al*., 2002; Wesselingh *et al*., 2006b), it is apparent that mudstone/claystone intervals represent retrogradational TST intervals followed by aggradational HST intervals. Well-expressed examples of both were seen in the wells. HSTs were generally interpreted from aggradational claystone intervals located above transgressive mudstone intervals and below progradational sandstone intervals. TST claystone/mudstone or coal intervals often directly overlay a coarsening upward RST sandstone interval. Mudstones/claystones deposited in TSTs and HSTs above potential flooding surfaces at TSs and MFSs were interpreted from their relative position within the short-term sequences, a combination of positive GR excursions and negative resistivity excursions, and additional information from the lithology logs and rock samples.

The studied formations are characterized by a lack of datable materials, and in general their ages have been unclear. For the Pebas Formation, only the age estimates derived from correlation of palynomorph zones (Hoorn, 1993) with marine successions in the Caribbean were available. We have attempted to make crude age calculations for the studied units. They are based on two age estimates (boundary of the *Crassoretitriletes* and *Grimsdalea* palynomorph zones coinciding with the CZ3-CZ4 boundary) at 12.5 Ma and a 36.3 Ma age for the (mean depth of the) lower Sandstone Member of the

Pozo Formation, being the average age of the overlap of two published radiometric ages (43 ± 9.9 Ma and 35.1 ± 4.4 Ma: Hermoza, 2005). Furthermore, two assumptions were introduced for these calculations: continuous deposition in the Marañon basin and constant sedimentation rates for the entire period. Both basin-wide and regional variation of tectonic subsidence and depositional rates did occur (Hermoza, 2005; Hermoza *et al.*, 2005). Furthermore, evidence for stratigraphic hiatuses exists, as well as some lateral variability of the depositional architecture within the studied formations, shown on seismic profiles (Hermoza, 2005). These alone did produce variation in sedimentation rates. It is also possible that the very different depositional regimes (e.g., marginal marine settings of subunit 1 of the Chambira Formation to fluvial regimes in the overlying subunit 2 and subunit 3 as well as in the Marañon Formation) may represent substantial different depositional rates. Despite the number and weakness of the assumptions, the model calculations give ideas about the approximate ages of the formations. With the lithological characterisation, assessment of boundaries between the lithological units and estimated ages we developed a lithostratigraphic framework.

Lithological description of the wells

Well Jibaro – A lithological interpretation of well Jibaro is given in Figure 3 and summarized in Table 2. Subunit 1 of the Chambira Formation (7200-7230 ft) is a thin fining-up sandstone interval. The boundary with the green glauconitic claystone/siltstone of the Pozo Formation is sharp and well expressed on the sonic log (Fig. 3). Subunit 1 rapidly passes into subunit 2 (5960 -7200 ft) that is dominated by reddish to varicoloured shaly claystones/siltstones containing anhydrite, and carbonate crusts and nodules. The boundary between subunit 2 and subunit 3 is located at the base of a shell-bearing

Table 2. Summary of lithological units in well Jibaro.

Well Jibaro

Depth (ft)	Lithology	Mollusc fossils	Interpreted depositional environment	Geological unit
1170-1000	Alternation of red-varicoloured claystone and whitish fine-grained lithic arenite with green minerals.	Few, mainly fluvial taxa.	Low-gradient meander belts and overbank areas of rivers draining volcanic active Andean hinterland.	MaraÒon Formation
2620-1170	Alternation of grey siltstone with carbonate concretions in some intervals, common blue-grey lithic arenites with some green minerals and lignite layers.	Admixture of fluvial taxa and endemic Pebasian taxa; between 1300 and 2250 ft Pebasian endemic taxa dominate.	Alternation of non-marine coastal plain, megalacustrine, some swamp and possibly floodplain environments.	Pebas Formation
3100-2620	Alternation of grey-green silt/claystone with carbonate nodules, lignite layers and shell beds.	Few Pebasian endemic taxa as well as fluvial taxa.	Alternation of non-marine coastal plain, megalacustrine and swamp environments.	Pebas Formation
3765-3100	Grey-green silt/claystone with some shell beds and some carbonate concretions.	Few Pebasian endemic taxa as well as fluvial taxa.	Alternation of non-marine coastal plain, megalacustrine, commonly flooded overbank and swamp environments.	Pebas Formation
4055-3765	Blue-grey lithic arenite with common green minerals; grey-green shales/siltstone with carbonate conretions.	Only strongly lithified and diagnetically altered fragments.	Alternation of meander belt, regularly flooded overbank, non-marine coastal plain, megalacustrine and swamp environments.	Pebas Formation
4695-4055	Grey silt/claystones; some lignite layers; few shell beds; very rare lithic arenites with green minerals.	Only strongly lithified and diagnetically altered fragments.	Alternation of non-marine coastal plain, megalacustrine, commonly flooded overbank and swamp environments.	Pebas Formation
5960-4695	Predominantly reddish-varicoloured silt/claystone with anhydrite and carbonate nodules and carbonate crusts alternating with greyish lithic arenites and shell carbonate layers.	Mention of *Turritella* in description (probably *Sheppardiconcha* spp.).	Commonly flooded overbank and meander belt environments in seasonal setting as well as lacustrine environments.	Chambira Fm., subunit 3
7200-5960	Varicoloured clay/siltstone, some carbonate nodules; few shell carbonate layers.	Mention of *Turritella* in description (probably *Sheppardiconcha* spp.).	Low-energy anastomosed channels and commonly flooded overbank environments in a seasonal setting.	Chambira Fm., subunit 2
7230-7200	Green-greyish white arenite with some green minerals; some claystone.	Not studied.	Marginal marine and coastal plain environments.	Chambira Fm., subunit 1

carbonate bed at 5960 ft. The reddish fine-grained deposits of subunit 2 remain to dominate in subunit 3, but there they are interlayered with sandstone beds. Carbonate or marl layers with shells (reported as *'Turitella'* and '*Viviparus*', but almost certainly composed of *Sheppardiconcha* and ampullariids) are quite common in the basal two thirds of subunit 3 (4695-5960 ft) of the Chambira Formation that contains substantial sandstone layers as well. Thick fining-up cycles, that show a bell-shape on the gamma ray, are present throughout subunit 3. The lowermost coal layer, marking the base of the Pebas Formation, is found at 4685-4695 ft and is located in a zone where sandstones become rare and anhydrite and carbonate concretions/crusts disappear. Within the Pebas Formation, carbonate concretions and anhydrite are reported around 1600 ft, and become common from 1440 ft upward. The uppermost coal layer, marking the Pebas Formation – Marañon Formation boundary is found at 1170 ft, shortly below the top of the well log (1000 ft).

Well Huayuri – A lithological interpretation of well Huayuri is given in Figure 4 and summarized in Table 3. The base of the Chambira Formation is sharp, and especially pronounced in the resistivity and sonic logs. Subunit 1 of the Chambira Formation (7788-7880 ft) is composed of greenish grey, glauconitic sandstones and siltstones. The subunit 1 – subunit 2 boundary is sharp. Subunit 2 (6315-7788 ft) is completely dominated by reddish claystones and mudstones with anhydrite, and carbonate nodules and crusts. From 7005 ft upwards, thin (typical <10 ft) carbonate layers with gastropods and thin sandstone layers with rare organic debris as well as green mineral grains occur sporadically. Fining-up cycles (up to *c.* 40 ft thick) are developed in subunit 3 of the Chambira Formation, but also present in the lower half of the Pebas Formation. The base of the Pebas Formation is located at the base of the lowermost coal layer at 4915 ft. The upper end of the well log is located within the Pebas Formation.

Well Capahuari – A lithological interpretation of well Capahuari is given in Figure 5 and summarized in Table 4. The boundary between the Chambira and underlying Pozo Formation (8974 ft) is sharp, and located at a clear break from dark-greenish grey glauconite bearing claystones and mudstones of the Pozo Shale Member to predominantly

Table 3. Summary of lithological units in well Huayuri.

Well Huayuri				
Depth (ft)	Lithology	Mollusc fossils	Interpreted depositional environment	Geological unit
3260-2000	Alternating light grey-green to varicoloured clay/mudstone; shell beds and lignite layers common; lithic arenite layers rare.	Admixture of fluvial taxa and endemic Pebasian taxa; above 2300 ft Pebasian endemic taxa dominate.	Alternation of non-marine coastal plain, megalacustrine and possibly some meander belts or marginal marine environments.	Pebas Formation
4025-3260	Dominantly clay/mudstone with some lignite layers and shell beds.	Admixture of fluvial taxa and endemic Pebasian taxa.	Alternation of non-marine coastal plain and megalacustrine environments.	Pebas Formation
4915-4025	Alternating light grey-green to varicoloured clay/mudstone, common lithic arenite layers (up to 25 ft); common lignites and intervals with common shell beds	Only strongly lithified and diagnetically altered fragments.	Alternation of megalacustrine, non-marine coastal plain, swamp, floodplain and meander belt environments.	Pebas Formation
6315-4915	Reddish-varicoloured claystone and siltstone with common anhydrite and carbonate concretions and crusts and common 10-45 ft thick light-grey greenish arenites; few shelly carbonate layers.	Not studied.	Commonly flooded overbank, lake and meander belt environments in seasonal setting.	Chambira Fm., subunit 3
7788-6315	Red-grey to varicoloured silt/claystone with anhydrite and carbonate nodules and crusts; very few lithic arenite layers; two thin shell beds.	Not studied.	Commonly flooded overbank to lake environments and low-energy anastomosed channels in seasonal setting.	Chambira Fm., subunit 2
7880-7788	Alternation of greenish-grey fine-grained lithic arenites with green minerals and white-grey shales.	Not studied.	Marginal marine and coastal plain environments.	Chambira Fm., subunit 1

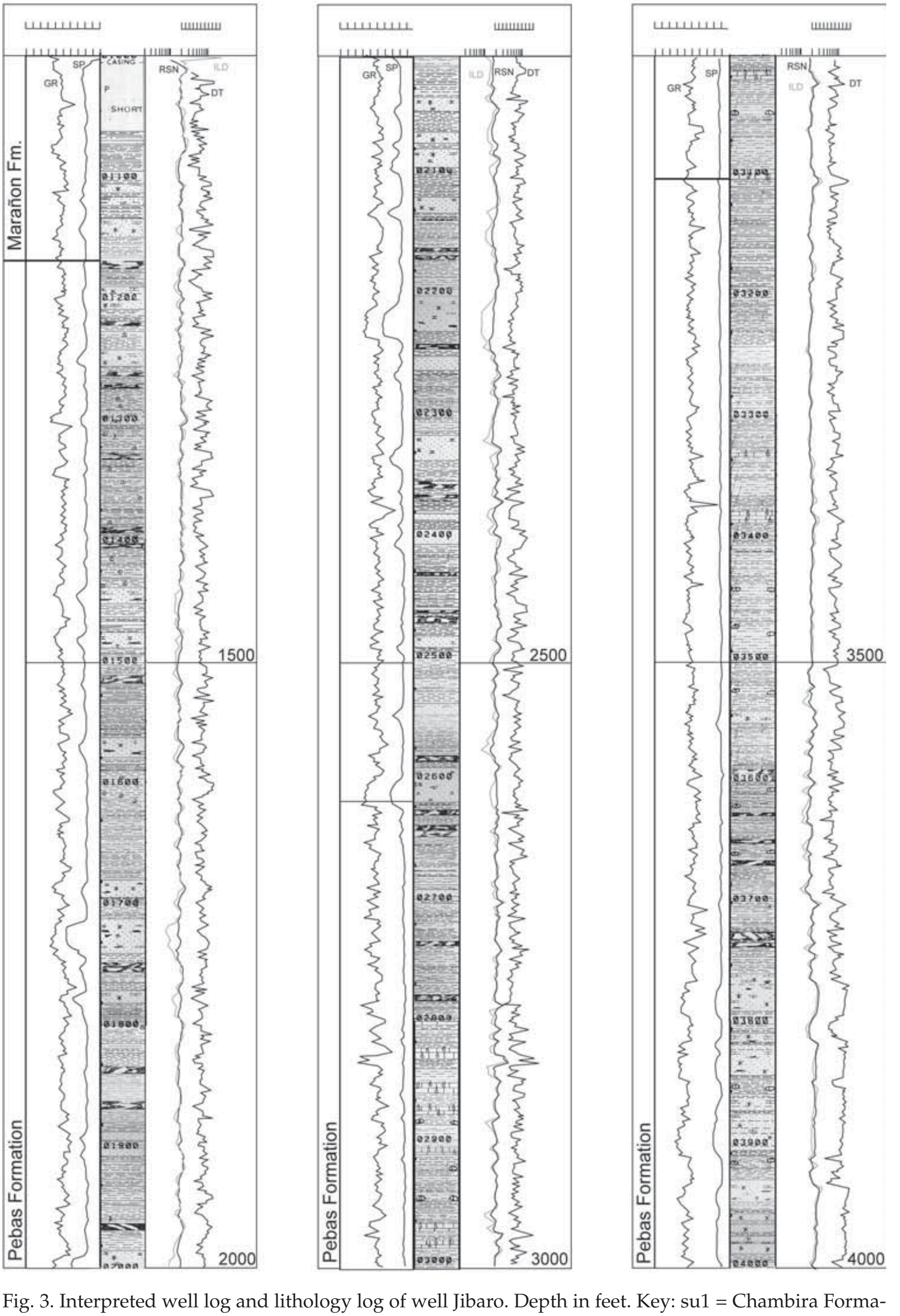
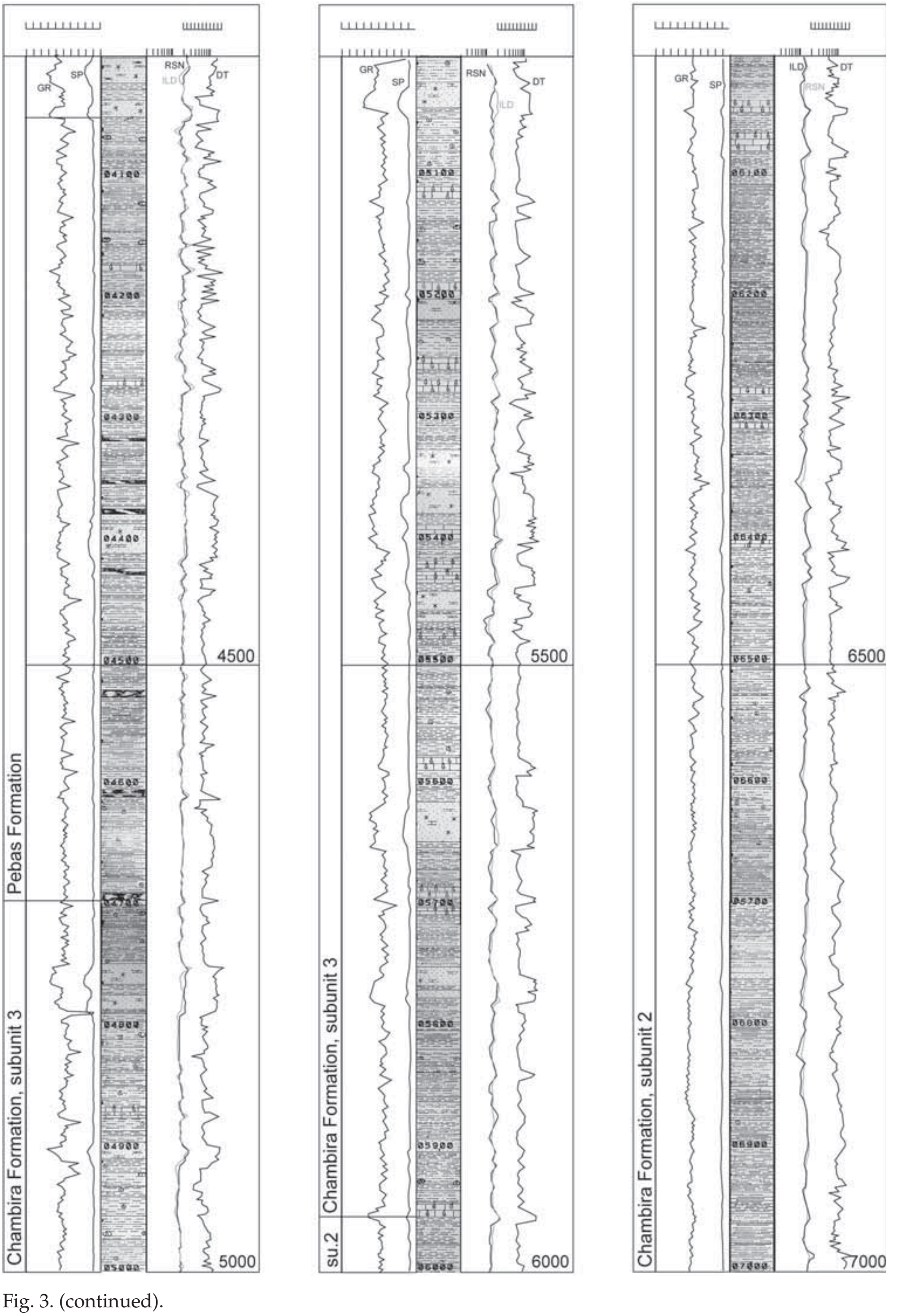


Fig. 3. Interpreted well log and lithology log of well Jibaro. Depth in feet. Key: su1 = Chambira Formation, subunit 1; su.2 = Chambira Formation, subunit 2.



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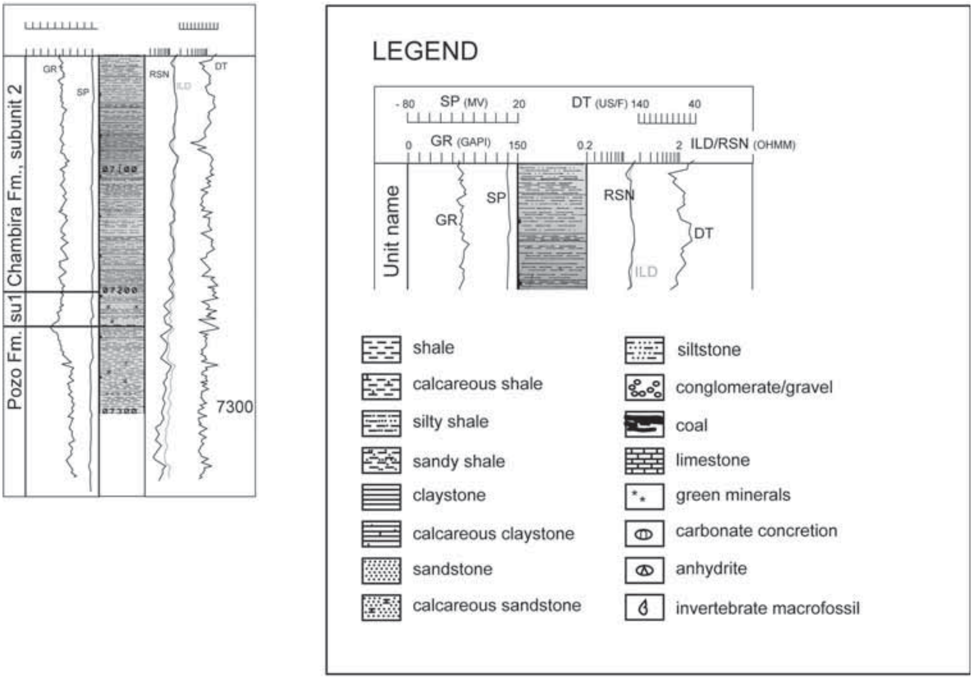


Fig. 3. (continued).

Table 4. Summary of lithological units in well Capahuari.

Well Capahuari Depth (ft)	Lithology	Mollusc fossils	Interpreted depositional environment	Geological unit
2335-2000	Alternation of 25-45 ft white fine grained lithic arenite layers and 30-150 ft intervals of reddish-grey to varicoloured claystone.	Absent.	Low-gradient meander belts of rivers draining volcanic active Andean hinterland.	MaraÒon Formation
3870-2335	Alternating light grey-green to varicoloured clay/mudstone, occuring lithic arenite layers; few mollusc layers, some lignite.	2350-2700 ft predominantly fluvial taxa; 2700-3450 ft species-rich endemic fauna; 3650-3870 ft mixture of Pebasian endemic taxa and fluvial taxa.	Alternation of non-marine coastal plain and megalacustrine environments.	Pebas Formation
4190-3870	Alternating grey clay/mudstone, thin interlaminated lignite layers and thin shell beds.	Few Pebasian endemic taxa as well as fluvial taxa.	Alternation of non-marine coastal plain, megalacustrine, swamp and possibly floodplain environments.	Pebas Formation
4875-4190	Grey-varicoloured silt and claystone with common lignites; anhydrite crusts rare; shell beds rare; two well developed lithic arenite layers.	Few Pebasian endemic taxa as well as fluvial taxa.	Alternation of megalacustrine, non-marine coastal plain, swamp and possibly floodplain environments.	Pebas Formation
5710-4875	Red-varicoloured sandy claystone lacking anhydrite and carbonate crusts; arenite layers rare.	Absent	Uncertain, possibly commonly flooded overbank, swamp and/or lacustrine settings.	?Pebas Formation
6765-5710	Red-varicoloured claystone with common carbonate and anhydrite crusts and concretions; arenites rare.	Not studied.	Commonly flooded overbank environments in seasonal setting.	Chambira Fm., subunit 3
7245-6765	Reddish-varicoloured claystone and siltstone with common anhydrite crusts and carbonate concretions and common 10-20 ft thick light-grey greenish arenites.	Not studied.	Commonly flooded overbank and meander belt environments in seasonal setting.	Chambira Fm., subunit 3
8850-7245	Reddish-varicoloured claystone and siltstone with common anhydrite concretions and carbonate concretions and crusts.	Not studied.	Commonly flooded overbank environments and low-energy anastomosed channels in seasonal setting.	Chambira Fm., subunit 2
8974-8850	Alternation of light-grey greenish fine-grained arenites with common green minerals and light-grey greenish non-calcareous shales.	Not studied.	Marginal marine and coastal plain environments.	Chambira Fm., subunit 1

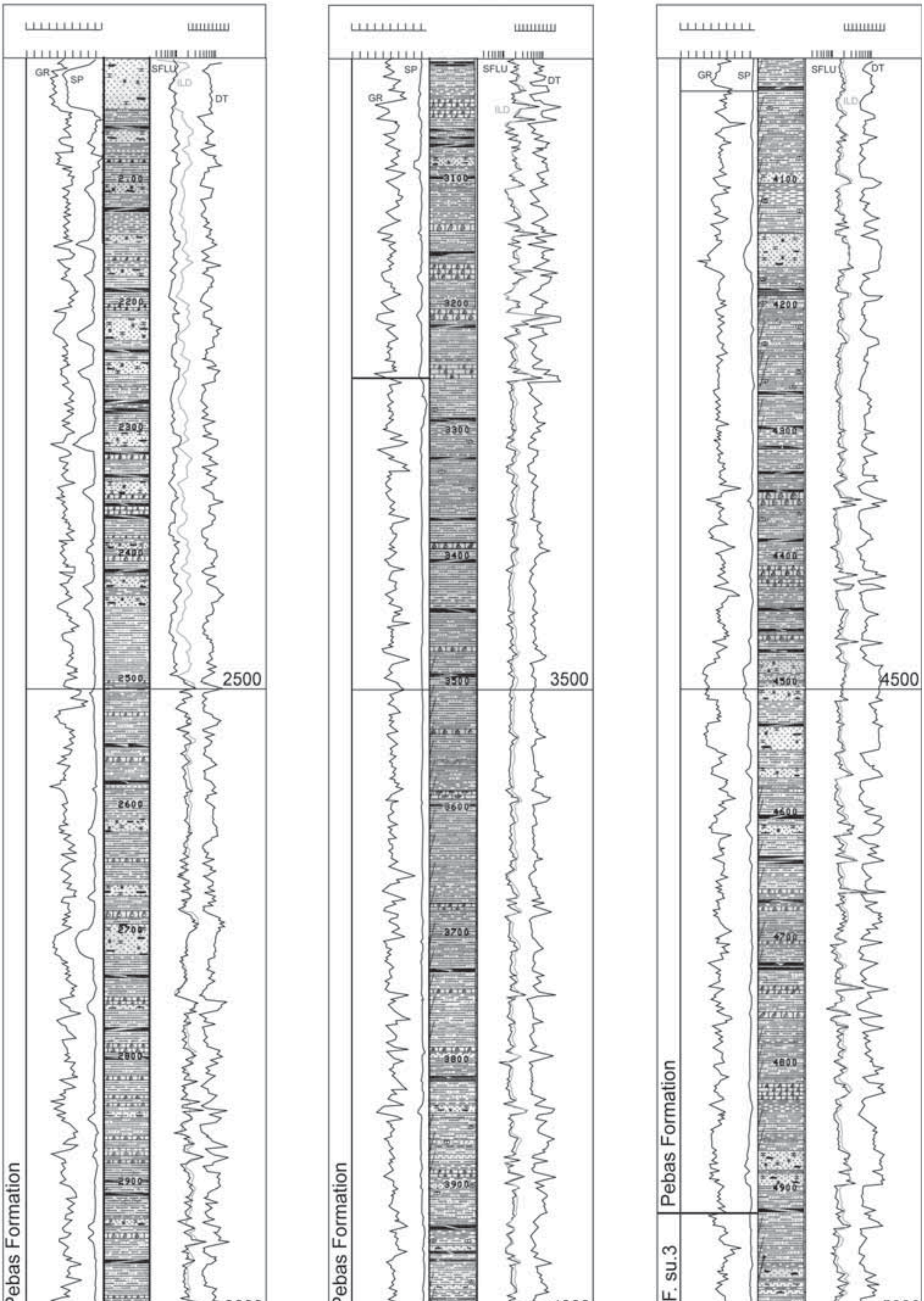


Fig. 4. Interpreted well log and lithology log of well Huayuri. Depth in feet. Legend in Figure 3 (read SFLU instead of RSN). Key: CF. su.3 = Chambira Formation, subunit 3; PF = Pozo Formation.

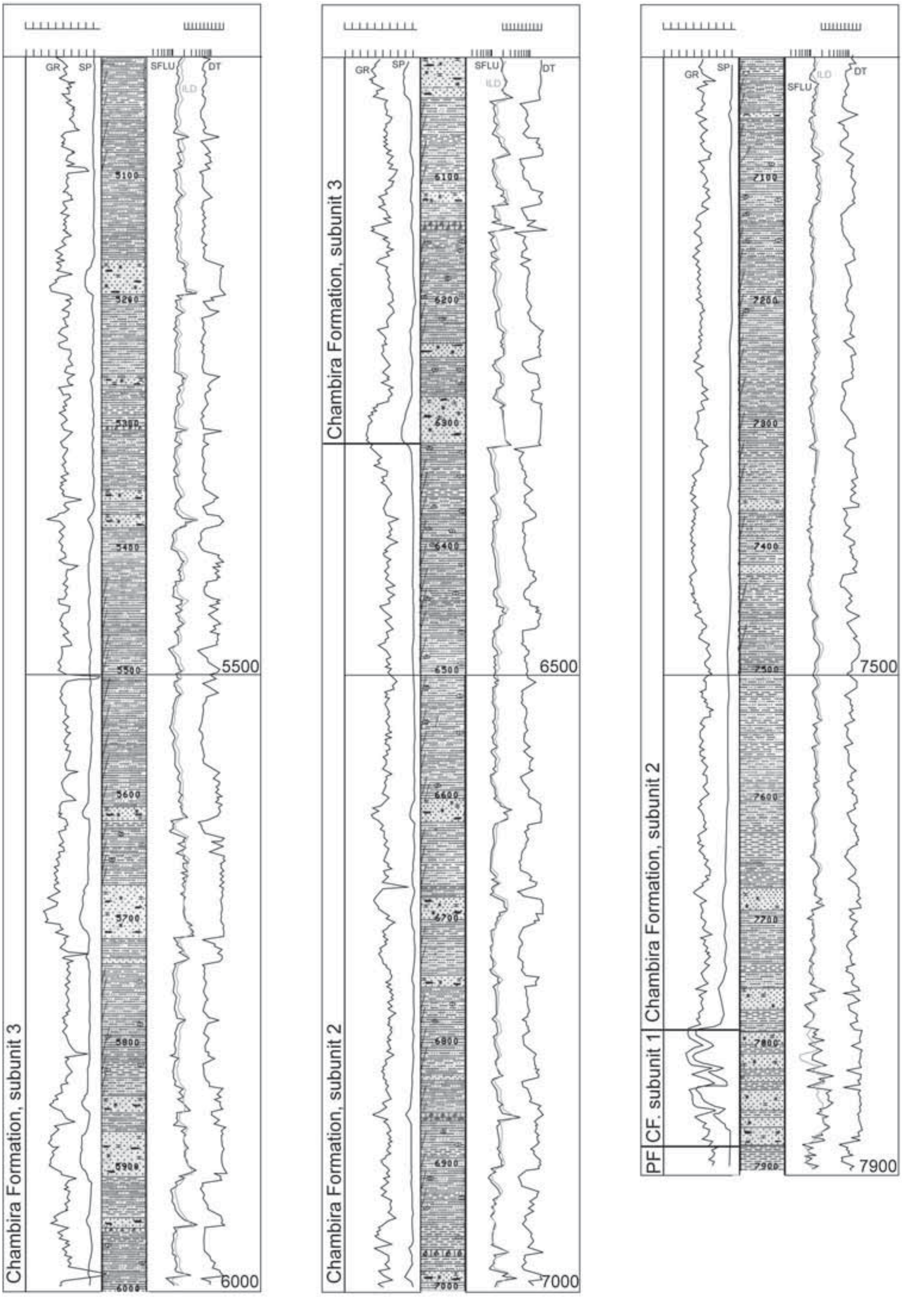


Fig. 4. (continued).

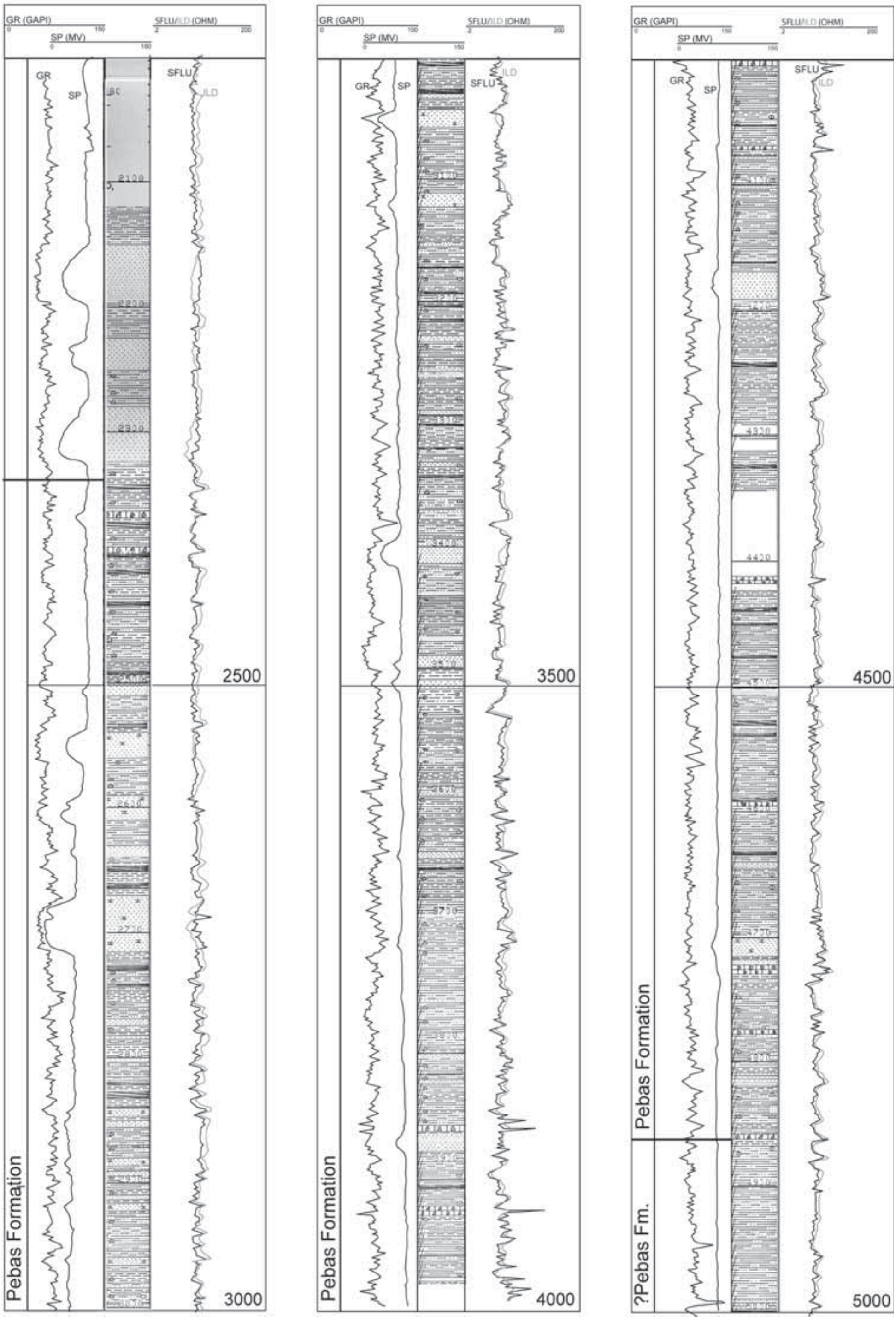
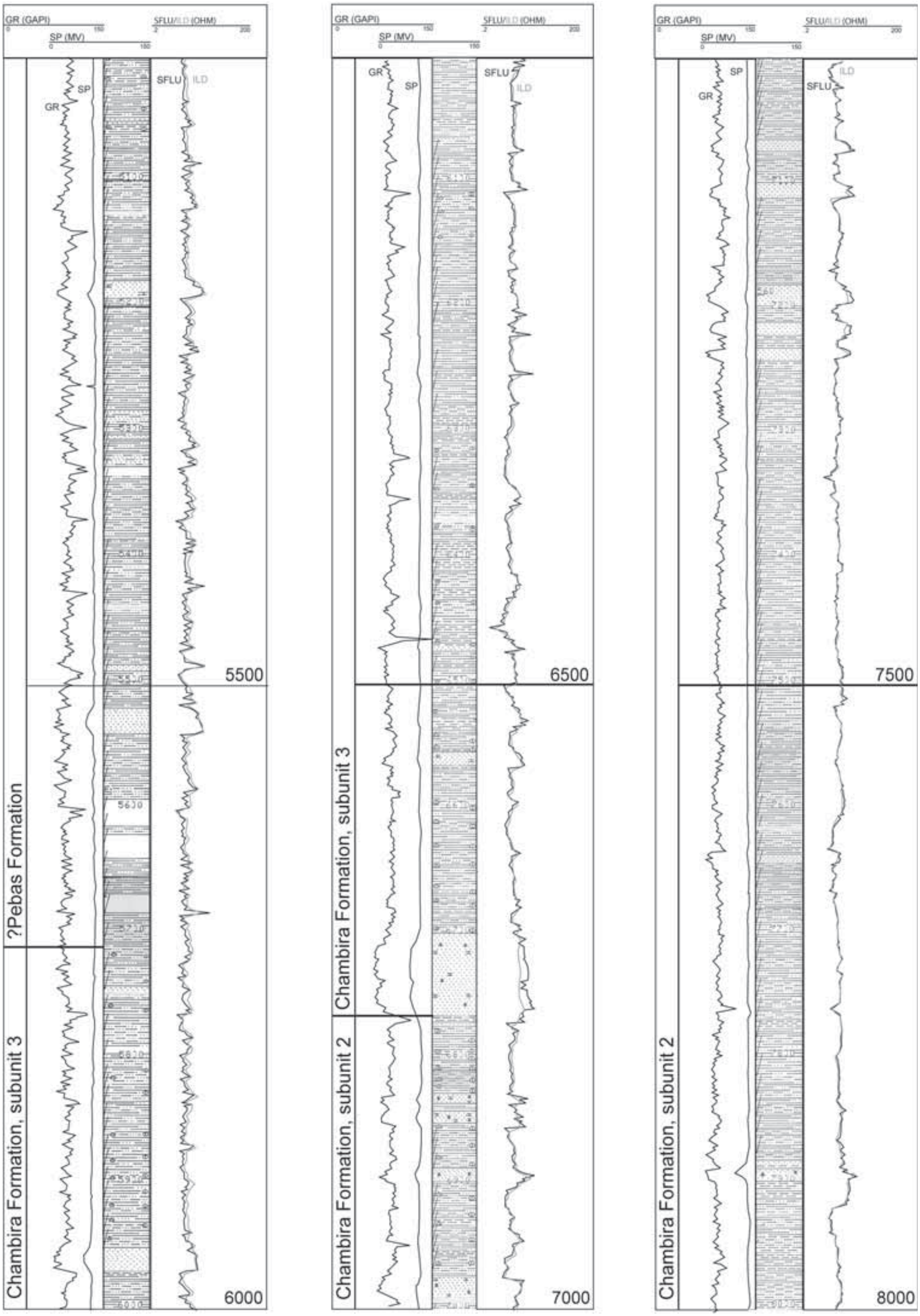


Fig. 5. Interpreted well log and lithology log of well Capahuari. Depth in feet. Legend in Figure 3.



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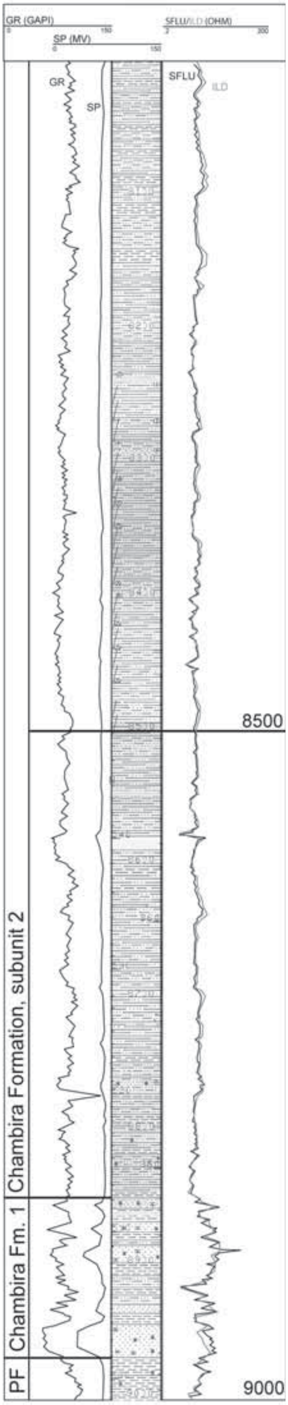

Fig. 5. (continued).

greenish-grey glauconite bearing sandstones and light grey shales of the base of the Chambira Formation. The top of the subunit 1 (at 8850 ft) is a sharp lithological transition from sandstone to shales that is well expressed in the resistivity curves. The boundary between the second and third subunit of the Chambira Formation at 6765 ft is located at the sharp base of a thick sandstone interval, and seen in clear breaks in the GR and resistivity curves. Subunit 3 of the Chambira Formation is characterized by several thick sandstone layers in the basal half, but otherwise dominated by reddish claystones and mudstones. The boundary between the Chambira Formation and the Pebas Formation is unclear in well Capahuari. From *c.* 4880 ft upwards, mollusc-bearing layers become common and coals also become common upward on the lithology log. However, the interval below 4880 ft bears very little information and, from correlations with wells Huayuri and Jibaro (see below), we would expect coals and shell beds possibly down to *c.* 5700 ft. A subtle lithology shift is seen at 5710 ft on the logs, where the common anhydrite, carbonate nodules and crusts become rare. We therefore think that the boundary between the Pebas and Chambira Formation in well Capahuari might be located at 5710 ft. The interval between 5710 ft and 4880 ft is attributed hesitantly to the Pebas Formation. Several fining-up sandstone intervals expressed with characteristic bell-shaped curves on the gamma ray and resistivity logs (at 5530 ft and 5190 ft) may represent meander belt depositional intervals. A similar lateral transition of Pebas Formation like lithologies of the Curaray Formation into fluvial deposits of the Arajuno Formation has been documented in the Oriente basin of Ecuador slightly to the north of the study area (Burgos, 2006). In well Capahuari, a sharp lithological transition at 2340 ft marks the boundary between the Pebas Formation and Marañon Formation. Below the boundary, greyish claystones, coals and shell layers are common. In the uppermost 100 ft varicoloured sedimentary rocks with carbonate concretions occur. Above it, thick sandstone and reddish claystones are dominant, and the GR and resistivity excursions become thicker.

Correlation between wells

Mollusc biozonation – The appendix lists the species found in the three boreholes. Table 5 lists the occurrence of stratigraphic indicative species in the wells and Table 6 summarizes the depth and thickness of the crude mollusc zones (CZ) in the wells. A westward structural dip of the zones is present in the wells that are located more or less perpendicular to the axis of the foreland basin (Hermoza, 2005). The depth below which compacted and more lithified molluscs occur is diachronic in respect with the CZ1-CZ2 boundary. In samples below CZ1, sporadically lithified mollusc fragments were seen in sandstone fragments. Some variation was observed in the thickness of the mollusc zones (Table 6). This variation is attributed to the low mollusc yield of the studied samples introducing some uncertainty as to the exact boundaries of the zones. Together with the boundary between the Pozo Formation and the Chambira Formation, the mollusc biozone boundaries were used to frame the well intervals for further correlation exercises.

Markerbed correlation – Coals could not be traced from well to well. The distribution of sandstone bodies (and sandy shell beds) in the three studied wells as interpreted from the well logs (Fig. 6) is vertically and laterally uneven. Subunit 1 of the Chambira Formation has several densely packed sandstone layers; some of these may form laterally persistent intervals, but not necessarily correlate individually. The overlying subunit 2 is almost devoid of sandstone layers and the few present cannot be correlated from well to well. Subunit 3 of the Chambira Formation is relatively rich in sandstone layers. In the Capahuari and Jibaro wells, the layers are common in the lower third of this subu-

Table 5. Last occurrence dates (LOD) of potential stratigraphic indicative species. Depths in ft. * = no samples available above level 2010.

Mollusc species	Capahuari	Huayuri	Jibaro
Dyris denticulatus Wesselingh	3950	3000	2700
D. lataguensis Wesselingh	3800	3050	2900
Cochliopina? *colombiana* Nuttall	3950		
Charadreon eucosmius (Pilsbry & Olsson)	3300	2450	2200
Sheppardiconcha colombiana (Nuttall)	4100	3100	
Sheppardiconcha lataguensis Nuttall		3350	2750
Sheppardiconcha tuberculifera (Conrad)	3050	2050	1950
Pachydon obliquus Gabb	2750	2050	1250
Pachydon cebada (Anderson)	3850	3300	2950
Pachydon hettneri (Anderson)	3850	3050	2950
top Pebasian molluscs	2350	2010*	1050
top compacted fossils	3600	2850	2750
base of apparent *in situ* faunas	4550	3850	3400

Table 6. Summary of molluscan zones in the studied wells. Depth in ft. Thickness of interval in brackets in ft. * = Large differences in thickness in CZ4 in the three wells are due to a lack of stratigraphic shallow samples in well Huayuri, resulting in a very thin CZ4.

	CZ 1.	CZ 2.	CZ 3.	CZ4	total thickness
Capahuari	3800-4550 (750)	3300-3800 (500)	3050-3300 (250)	2350-3050 (700)	1950
Huayuri	3000-3850 (850)	2450-3000 (550)	2050-2450 (400)	2010-2050 (40*)	1740*
Jibaro	2700-3400 (700)	2200-2700 (500)	1950-2200 (250)	1050-1950 (900)	2350

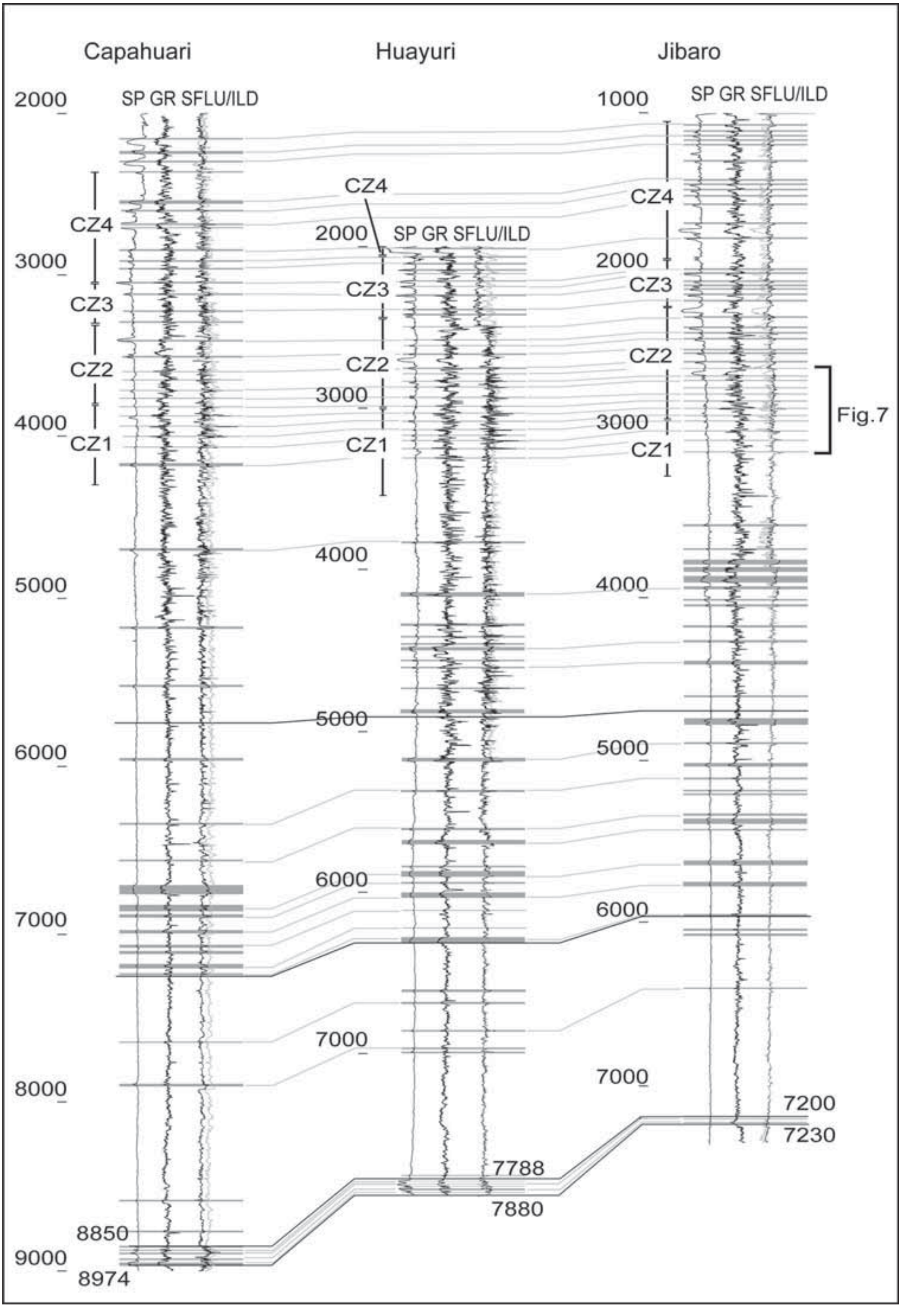

Fig. 6. Sandstone layers and sandy shell beds as interpreted from well logs. Depth in feet.

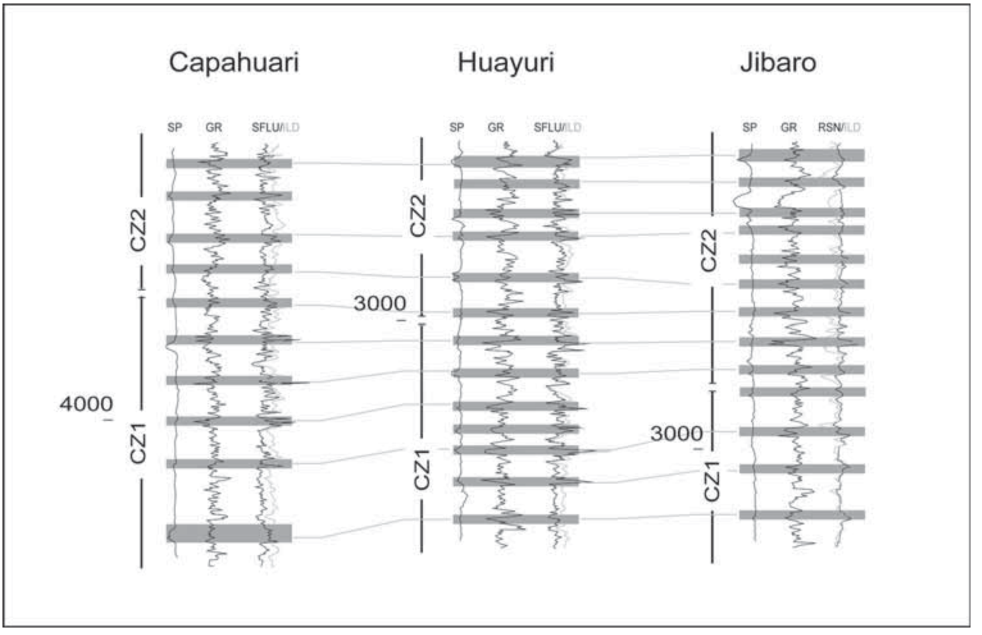

Fig. 7. Detail from Fig. 6. Depth in feet.

nit; in the Jibaro well they are commonest in the upper half of the subunit. Several of the sandstone intervals appear to be laterally traceable, but we doubt whether this also applies to individual layers. Interestingly, several of the sandstone layers appear to pass laterally (towards the east) into mollusc-rich carbonates or marls. Sandstone layers in the lower part of the Pebas Formation (below the base of CZ1) are rare and occur unevenly in the vertical succession as well as in laterally adjacent positions. Relatively densely packed sandstone intervals in Huayuri (*c.* 4400-4900 ft) and Jibaro (*c.* 3700-4100 ft) that are laterally not well traceable represent localized sandstone bodies. The interval covering the top of CZ1 and the base of CZ2 in the Pebas Formation is very rich in sandstone and sandy shell layers that also appear to be regularly spaced and in general laterally persistent (Fig. 7). In the remainder of the Pebas Formation, sandstone layers are common and often appear to be traceable in adjacent wells.

Several sandstone layers occur in the small available interval of the Marañon Formation in well Capahuari could be matched with sandstone layers in the uppermost part of the Pebas Formation in well Jibaro. The presence of intervals with more densely packed sandstone layers in subunits 2 and 3 of the Chambira Formation at different stratigraphical levels that are laterally not traceable, and have often a typical bell-shaped gamma ray curve, represent the local presence of channel belts of anastomosing or meandering rivers. The sandstone layers are used to refine correlations between the wells in subunit 1 of the Chambira Formation, the upper half of the Pebas Formation and the Marañon Formation.

The density of mudstones/claystones deposited in TSTs and HSTs above potential flooding surfaces at TSs and MFSs is unequally distributed vertically. In subunit 1 of the Chambira Formation, several densely spaced surfaces occur, but in the overlying

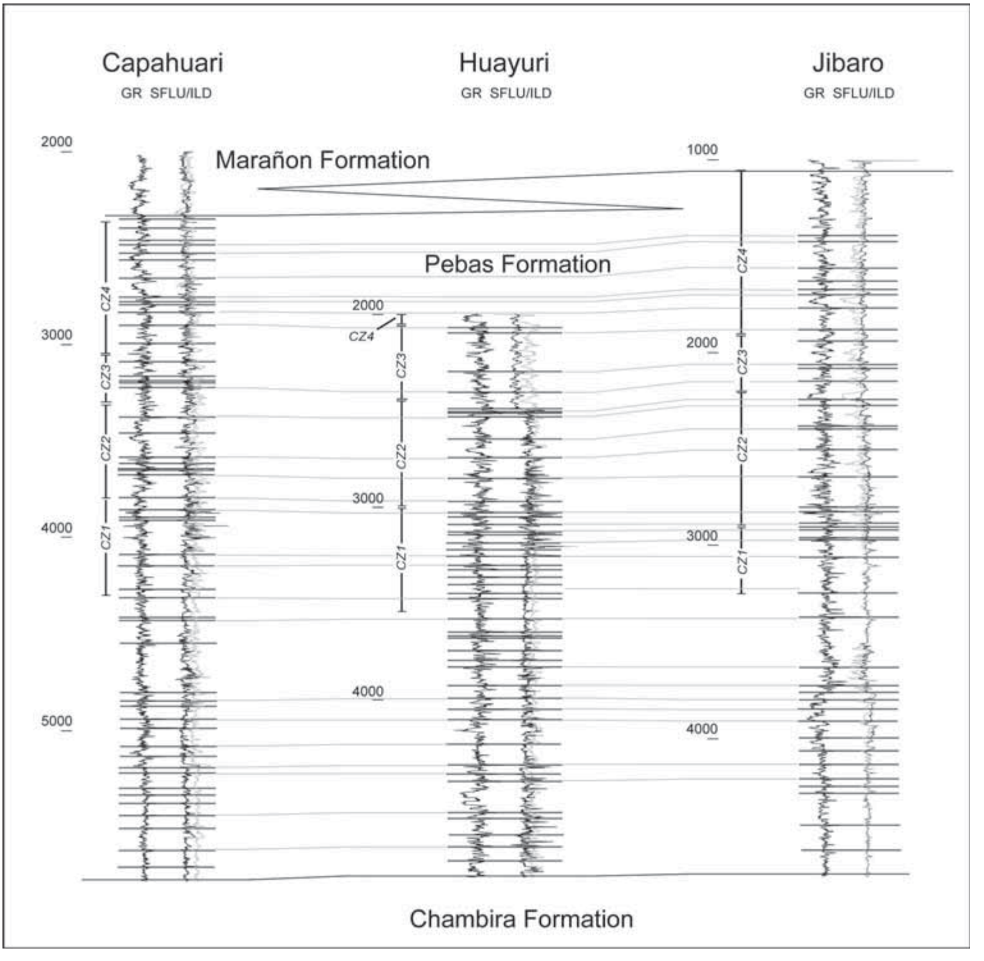

Fig. 8. Potential flooding surfaces in the Pebas Formation. Depth in feet.

subunits 2 and 3 they are very rare, and laterally not persistent between wells, probably because of their poor development in fluvial-dominated environments. In the Pebas Formation, flooding surfaces are common and densely spaced (Fig. 8). Correlation between wells is possible for many of the intervals. With such a dense occurrence of TSs and MFSs, the possibility of quasi-correlation must be considered, but many correlations match with those (independently) proposed for the sandstone horizons included in RSTs and LSTs. In the upper part of the Pebas Formation the density of flooding surfaces is higher than in the lower part, probably due to de establishment of permanent lake-wetland environments more susceptible to short-term base level change.

Age calculations and stratigraphic model

The assumption-laden age calculation model provides informed estimates of the approximate ages of the formations (Table 7). Calculated deposition rates of the Cham-

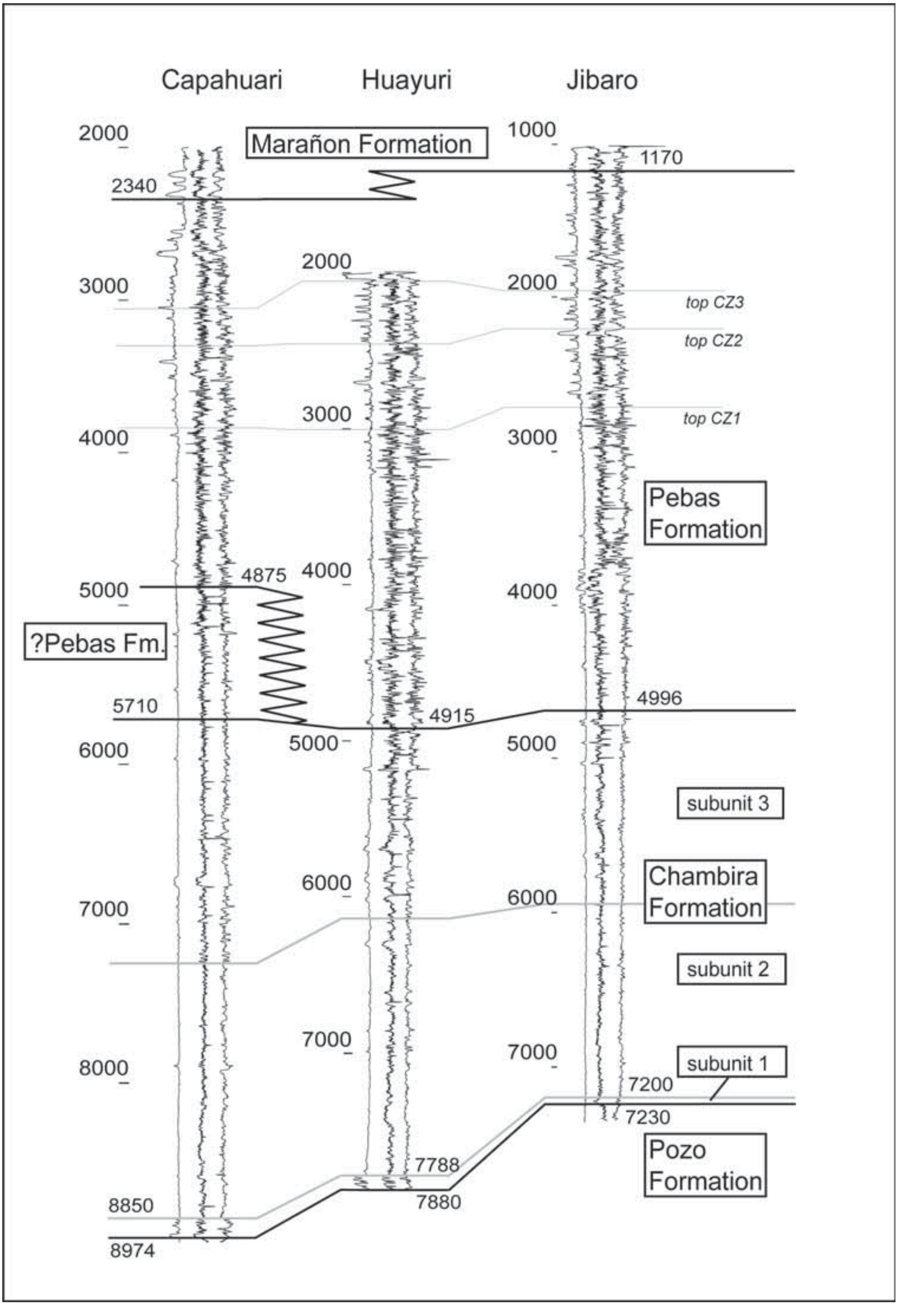

Fig. 9. Stratigraphic framework for the studied wells. Depth in feet.

bira-Pebas interval are 267 ft/Ma for well Capahuari, 265 ft/Ma for well Huayuri and 241 ft/Ma for well Jibaro. The age of boundary between the Chambira and the Pozo formations from the model calculations (34.5-34.7 Ma) is near the base of the Rupelian (at 33.9 Ma). In these calculations, the Chambira Formation (34.5/34.7 - 22.5/23.9 Ma) covers more or less the Oligocene (33.9-23.0 Ma). The age of base of the Pebas Formation differs somewhat between the three wells, but is placed near the Chattian-Aquitanian boundary. The Pebas Formation was deposited during the Early to early Late Miocene. From the calculations, the top of the Pebas Formation is suggested to be somewhat diachronic, becoming younger eastward. The upper age estimate for the Pebas Formation (9.3 Ma) comes close with the onset of modern Amazon River system, as dated by the influx of Andean derived Amazonian sediments in the Atlantic Ocean, at slightly older then 8 Ma (Harris & Mix, 2002). The model ages for the Pebas Formation (*c.* 23-9 Ma) do concur well with age estimates for the Curaray Formation of eastern Ecuador (25-6 Ma) that is considered an equivalent of the Pebas Formation (Burgos *et al.*, 2005; Burgos, 2006). The latter estimates are based on a number of radiometric ages of lateral formations, whose stratigraphic boundaries and correlations with the Curaray Formation are in need of further elaboration.

Table 7. Model age calculations for the studied units. Basic data and assumptions are discussed in the text.

	Capahuari	Huayuri	Jibaro
Top Pebas Formation	2400ft: 9.8 Ma	not available	1050ft: 9.3 Ma
Top Chambira Formation	5710ft: 22.5 Ma	4915ft: 23.3 Ma	4969ft: 23.9 Ma
Top Pozo Formation	8974ft: 34.7 Ma	7880ft: 34.5 Ma	7230ft: 34.5 Ma
Top Sand Mbr., Pozo Fm.	9344ft: 36.1 Ma	8273ft: 35.9 Ma	7590ft: 35.9 Ma

Figure 9 presents a stratigraphic model for the studied boreholes. The glauconitic shales of the upper part of the Pozo Formation are considered to represent offshore marine settings in a HST. Subunits 1 and 2 of the Chambira Formation are interpreted to form a RST, subunit 1 representing shoreface and coastal plain, and subunit 2 distal floodplain settings with a few anastomosing or meandering channels. The third subunit of the Chambira Formation was deposited in meandering channel belts and floodplain settings, representing aggradation in a LST. The lower half of the Pebas Formation, deposited in fluvial floodplain, non-marine coastal plain and lacustrine settings, is interpreted as a TST. The upper half of the Pebas Formation, with predominant lacustrine deposits, is interpreted as a HST. Finally, the fluvial deposits of the lower part of the Marañon Formation are included in a RST.

Discussion

Lithological definition of the geological units – The Chambira Formation consists of red-varicoloured claystone and siltstone with common white anhydrite and carbonate crusts and concretions; grey-greenish, fine-grained arenites occur. The base of the Chambira Formation in the studied wells, as well as in wells published by Hermoza (2005), is sharp. Subunit 1 is composed of light grey-greenish, very fine- to fine-grained lithic arenites containing green minerals, alternating with light grey to greenish non-calcareous shales with some pyrite and mica. The subunit decreases in thickness from west to east in the studied wells and, from the successive coarsening up to fining up trends, the former missing in the eastern wells, it appears that this regressive subunit overlays a hiatus. Subunit 2 of the Chambira Formation is composed of red(dish)-varicoloured claystone and siltstone with common thin, grey-white anhydrite and carbonate crusts and concretions; light greenish-grey-varicoloured very fine- to fine-grained arenites are very rare. Subunit 3 is dominated by red-varicoloured claystone that is not (or only slightly) calcareous containing common anhydrite, thin caliche-like crusts and carbonate concretions. Light greenish-grey to varicoloured, fine- to very fine-grained lithic arenite layers occur.

The Pebas Formation is dominated by grey-blue smectite-rich mudstones and claystones, with minor interbeds of grey feldspar-rich sandstones, brown-black coals and organic-rich claystones. In the upper half of the Pebas Formation, sandstone and sandy shell beds that are usually well expressed on the gamma ray and resistivity logs are common. Carbonate fossils are common throughout the Pebas Formation. Lithology types typical of the Chambira Formation (anhydrite-bearing and carbonate encrusted reddish siltstones and mudstones) occasionally occur in the lower part of the Pebas Formation, indicating a transitional change in depositional regimes of the two formations.

The Marañon Formation consists of an alternation of whitish fine- to very fine-grained lithic arenites and reddish-grey to varicoloured non-calcareous claystone. Anhydrite and carbonate crusts and concretions occur. The rare occurrence of similar lithologies within the upper part of the Pebas Formation indicate a gradual transition of the depositional regimes of both formations.

The Chambira Formation has been formally defined by Kummel (1948) and the status of the poorly defined Marañon Formation cannot be addressed with the incomplete well data here. The Pebas Formation is a name widely used in the literature (Guizado, 1975; Petri & Fulfaro, 1983; Hoorn, 1993; Hoorn *et al.*, 1995; Räsänen *et al.*, 1998; Gingras *et al.*, 2002; Wesselingh *et al.*, 2002; Vonhof *et al.*, 1998, 2003, to name but a few). Despite being a very characteristic and well recognizable unit, it lacks a proper description and a type section. In Brazil, the Pebas Formation has been often included in the Solimôes Formation (Hoorn, 1993), that itself is poorly understood, and whose type section (well 2RJ1AM; Eiras *et al.*, 1994) includes likely Paleogene up to Late Miocene formations. The Curaray Formation, the Ecuadorian equivalent of the Pebas Formation, also lacks a proper description and definition. Below, suggestions are made for the definition of the Pebas Formation.

No formal type section has been established for the Pebas Formation. We propose that well Jibaro, with its comparatively distinct upper and lower boundaries is an appropriate candidate for a main reference section, but a type section for typical Pebas Formation lithologies from an exposure in the Pebas area should also be considered. The Pebas Formation as indicated herein is found in outcrops and in the subsurface of the Solimôes basin and Acre basin (Brazil), the Ucayali basin and Marañon basin (Peru), the Oriente basin (Ecuador) and the Putumayo basin (Colombia). Furthermore, the formation covers a pericratonic zone in southeastern Colombia and adjacent Brazil, termed the Caqueta platform by Wesselingh *et al.* (2006a). The 1074 m thickness found in well Jibaro is so far the largest thickness documented for the Pebas Formation. In the

Solimões basin, the formation is typically up to *c.* 350 m thick (Hoorn, 1993). In the Caqueta platform region the Pebas Formation directly overlays Palaeozoic or Precambrian basement or the Early Miocene Mariñame unit (Hoorn, 1994), that continues in adjacent Brazil as the poorly defined Ramon Formation (Hoorn, 1993). In the Subandean basins the Pebas Formation overlies the Chambira Formation. In the wells studied herein the base of the Pebas Formation appears conformable. In the Subandean zone the Pebas Formation grades laterally into fluvial formations of Andean origin, like the Ipururo Formation in Peru (Hermoza *et al.*, 2005) and the Arajuno Formation in Ecuador (Burgos, 2006). In southeastern Colombia the Pebas Formation changes laterally to the Apoporis Sandstone unit that is dominated by fluvial sandstones of cratonic rivers draining the Guyana Shield (Hoorn, 2006). The age of the Pebas Formation is estimated to cover the Early Miocene up to the early Late Miocene. The formation was deposited in a complex system of shallow lakes and wetlands with intermittent swamps, non-marine coastal plains and some fluvial plains. Table 8 summarizes the major lithological differences between the Marañon, Pebas and Chambira Formations as found in the studied wells, Table 9 summarizes the depth of the proposed lithological boundaries in the wells and Table 10 summarizes the stratigraphic thickness of the units.

Table 8. Lithological differences between Chambira, Pebas and Marañon formations. [1]Carbonate fossils in the form of whitish-cream shell beds with an earthy or tuff texture from which *Turitella* (likely cerithoideans such as *Sheppardiconcha* spp.) and *Viviparus* (possibly Ampullariidae) are recorded on the lithology descriptions of the well log. [2]Carbonate fossils in the form of dispersed shells and ostracods as well as shell beds with a great variety of colours and textures.

	Chambira Fm.	Pebas Fm.	Marañon Fm.
lignite/coal	very uncommon	common	rare
carbonate fossils	uncommon[1]	abundant[2]	absent or rare
predominant lithology	siltstone-mudstone	siltstone-mudstone	sandstone-siltstone
predominant colours	reddish	grey-blue	reddish grey
anhydrite	common	rare	occurring
carbonate nodules/crusts	common	rare	occurring

Table 9. Suggested boundaries of lithological units.

	Capahuari	Huayuri	Jibaro
Base Marañon Formation	2335 ft	Absent	1170 ft
Base Pebas Formation	5710 ft	4915 ft	4695 ft
Base Chambira Fm., subunit 3	6765 ft	6315 ft	5960 ft
Base Chambira Fm., subunit 2	8850 ft	7788 ft	7200 ft
Base Chambira Fm., subunit 1	8974 ft	7880 ft	7230 ft

Table 10. Stratigraphic thickness of the units.

	Capahuari	Huayuri	Jibaro
Pebas Formation	3375 ft (1029 m)	>2915 ft (>889 m)	3525 ft (1074 m)
Chambira Formation	3264 ft (995 m)	2965 ft (904 m)	2535 ft (773 m)
subunit 3	1535 ft (468 m)	1400 ft (427 m)	1265 ft (386 m)
subunit 2	1605 ft (489 m)	1473 ft (449 m)	1240 ft (378 m)
subunit 1	124 ft (38 m)	92 ft (28 m)	30 ft (9 m)

Lateral continuity within the Pebas Formation – In the Pebas Formation, potential flooding surfaces (TSs and MFSs) are common and densely spaced. They occur in variable numbers vertically as well as laterally (Fig. 8). Correlation of flooding surfaces between wells is possible for many of the intervals, but with a dense occurrence of such surfaces the possibility of quasi-correlations must be considered. Many of the suggested correla-

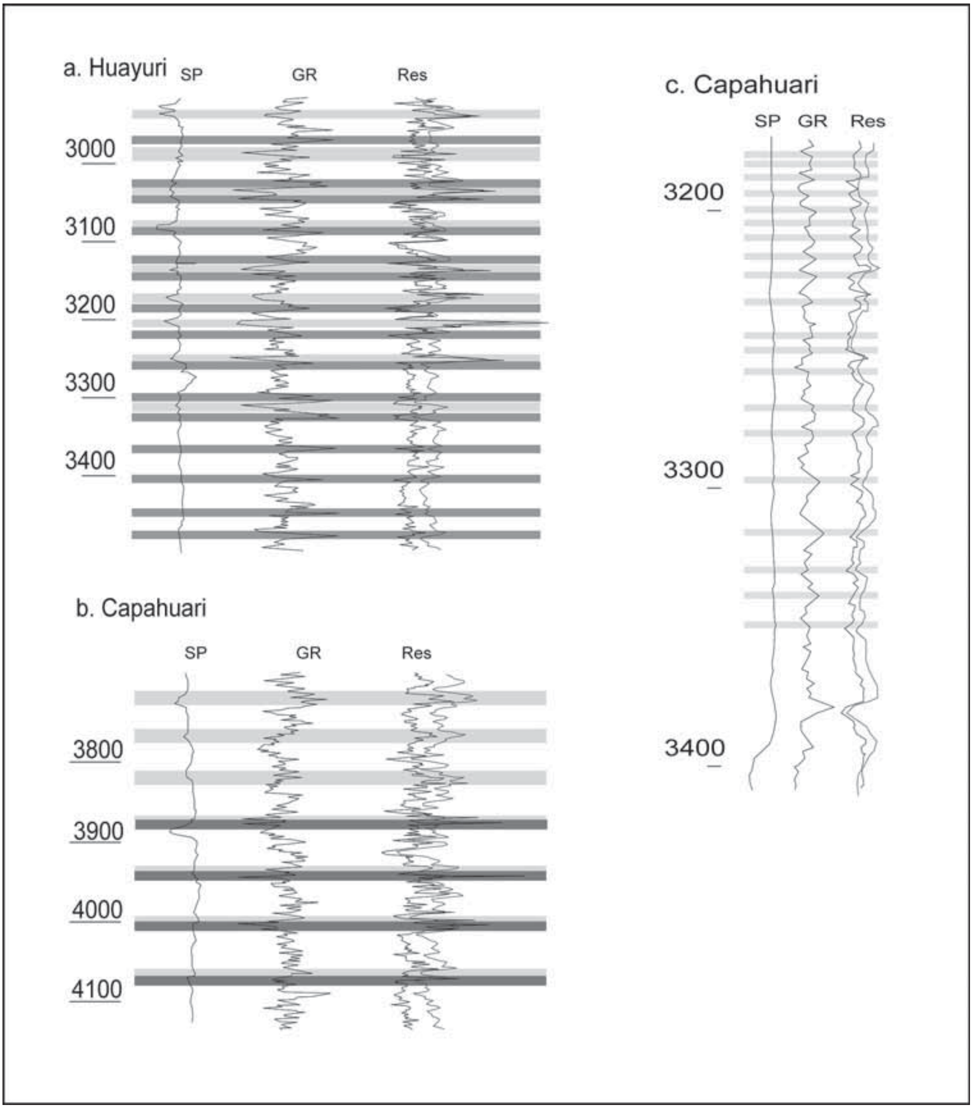

Fig. 10. Examples of apparent regularly recurring lithologies. a, Huayuri, Pebas Formation. Densely spaced flooding surfaces (dark grey), recurring at average 36 ft intervals, and less regular sandstone intervals (light grey) are indicated. b, Capahuari, Pebas Formation. Recurring sandstone (light grey) and shell beds (dark grey), with intervals between 60 and 70 ft. c, Capahuari, Pebas Formation. Densely spaced zig-zag patterns. In the upper part the distance between successive spikes averaging between 6 and 7 ft, in the lower part *c.* 12 ft.

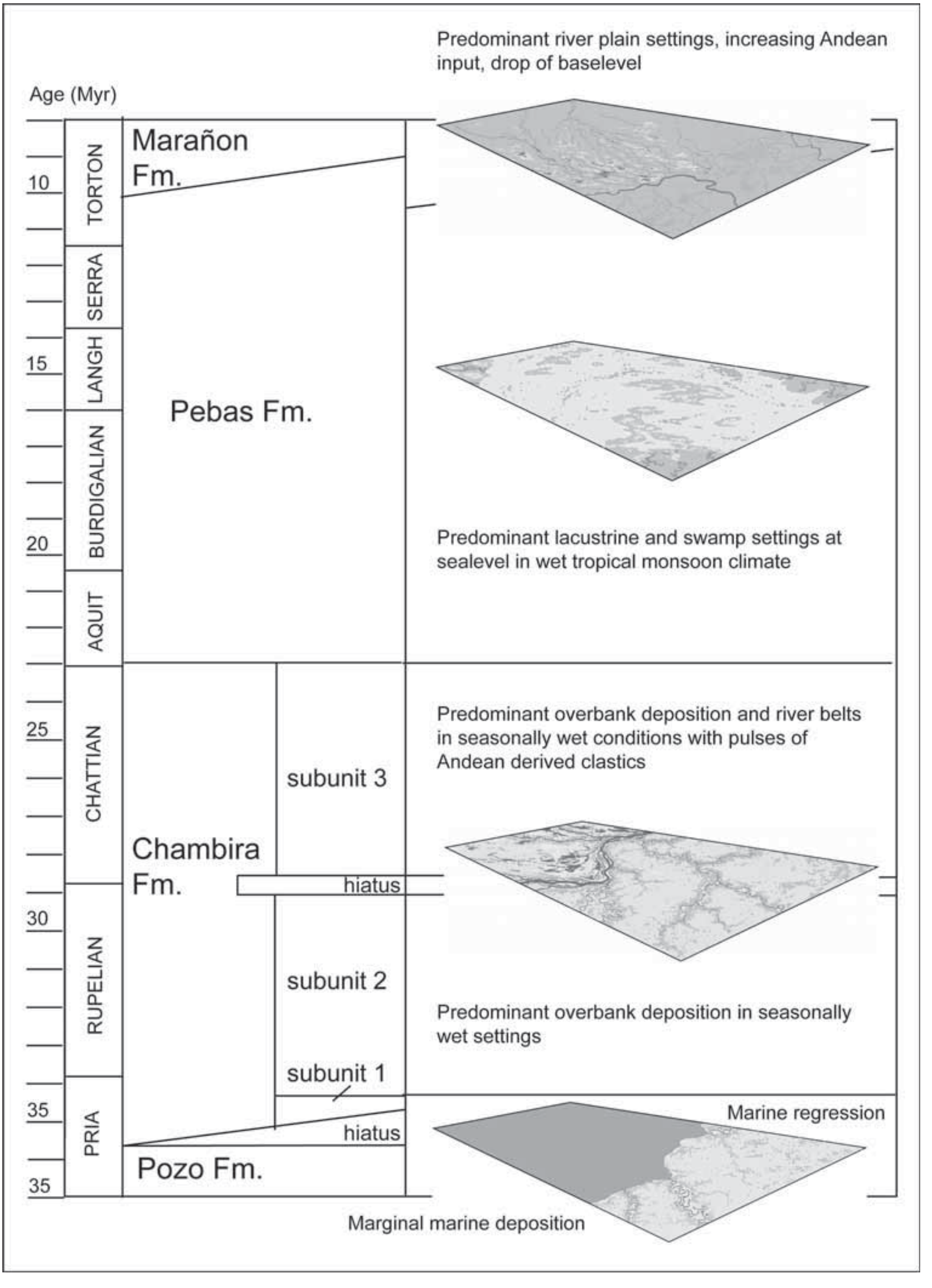

Fig. 11. Depositional model for the Oligocene-Miocene of the study area. Ages in Ma.

tions match with those (independently) proposed for the sandstone intervals. However, connection of aquatic habitats within the Pebas system may have been more common on smaller time scales. In a number of wells, intervals with a fine-scaled saw-tooth pattern on the gamma ray were observed. Figure 10c shows an example from well Capahuari, where distances between successive fine-grained intervals in the interval 3180-3270 ft b.s. are approximately 6-7 ft and between 3270 and 3350 ft b.s. approximately 12 ft, with corresponding calculated time intervals being 24 kA and 42 kA, respectively. The thicknesses match those of sequences studied in outcrops (Räsänen *et al*., 1998; Gingras *et al.,* 2002; Vonhof *et al.,* 2003; Wesselingh *et al*., 2006b). The calculated durations are close to 23 kA of precession cycles and 41 kA of obliquity cycles, making some sort of orbital-control over the formation of such sequences entirely feasible.

Other apparent depositional cycles –Various instances of regularly recurring layering reflect possible depositional cyclicity in the studied wells (Fig. 10). In well Huayuri (Fig. 10a), 15 potential flooding surfaces are present in the Pebas Formation between 3000 and 3400 ft. Using average depositional rates from the calculation model outlined before, the average duration between successive flooding surfaces would be 135 kA. This is close to an eccentricity cyclicity of 126 kA that occurred during the Miocene (Shackleton *et al*., 1999). But caution is warranted for the over-interpretation of apparent regularly recurring lithologies in terms of orbital processes. The apparent very regular occurrence of sandstone layers and shell beds (the latter with 65-68 ft distance between) in Capahuari (Fig. 10b) is calculated to represent 218 kA intervals. These cannot be matched to the duration of known Miocene orbital cycles (Shackleton *et al*., 1999).

Type and scale of depositional processes – A number of processes have shaped the Pebas system during the Miocene in western Amazonia (Fig. 11). The Andean uplift and the subsidence of Andean foreland basins (and pericratonic margins), was the overall driving force behind the presence of large scale fluvial and lake/wetland systems during the Oligo-Miocene in western Amazonia (Hermoza, 2005; Hermoza *et al.*, 2005; Burgos, 2006). These processes provided accommodation space and at the same time delivered huge quantities of erosive products, from the emergent Andes and the cratonic regions to the east, to form and fill the system. Variations in regional subsidence and uplift patterns existed during the Oligo-Miocene within western Amazonia (Hermoza, 2005; Hermoza *et al.,* 2005). Within the foreland basin, Hermoza (2005) showed the presence of low uplifts of tens of kilometres width; similar low domes exist nowadays to the northeast of Yurimaguas, Loreto, Peru. Variation of regional subsidence was also a major controlling factor in the shaping of portals between western Amazonia and the marine realm (Llanos basin, East Venezuela basin, Maracaibo basin; Lundberg *et al*., 1998). River and delta lobe avulsion should also have played a role in the system, although we only find minor evidence for localized channel-belt build-up and abandonment during deposition of the lower half of the Pebas Formation. The clear expression of regularly recurring, possibly orbital driven, depositional sequences could occur only in places where enough accommodation space was present.

Denudation of the hinterland also played an important role in shaping the balance between accommodation and infill. Rates of erosion are dependent on uplift, but are also linked to precipitation regimes that vary on orbital (Milankovitch) timescales (Kaandorp *et al*., 2005). Increased seasonality, with larger variation between dry and wet seasons in the Andean hinterland, may have produced larger quantities of relatively coarse-grained erosion products that were discharged into the foreland basin zone. Finally, base level variation played a major controlling role in shaping the system. Episodically, the system was located at sea level and connected to the sea. During such episodes, eustatic variation controlled base level change. From the model age calculations it emerges that the marine environments of the Pozo Formation and the marginal marine environments of the base of the Chambira Formation concur with eustatic highstands of the latest Eocene (Priabonian) and Early Oligocene (Rupelian: Hardenbol *et al*., 1998; but see Miall, 1997, for a critical review of the underlying methodology). However, calculated ages of subunit 2 of the Chambira Formation, for which no extensive marine influence has been demonstrated in the studied wells, also fall within the Rupelian highstand (Fig. 11). This indicates either tectonic uplift in the foreland basin, increased sediment input or insufficient age estimates for subunit 2 of the Chambira Formation. Indications for low base levels during deposition of most of subunit 3 of the Chambira match well with eustatic low stands during the Chattian (Hardenbol *et al*., 1998). Estimated ages for base level highstands as interpreted for the lower part of the Pebas Formation concur well with Aquitanian eustatic highstands. Pebasian faunal diversifications occurred at the same time that base level highstands became very common about halfway in the Pebas Formation. This stratigraphic interval conforms more or less eustatic highstands covering the latest Early Miocene and the early-middle Middle Miocene. Eustatic sea level dropped in the course of the Serravallian (Hardenbol *et al*., 1998), but base levels remained high in the Pebas system until the early Tortonian. For example, pearly freshwater mussels are common in fluvial influenced settings in the Pebas Formation, but very rare in lacustrine settings (Wesselingh *et al*., 2002); they are almost absent in the later part of CZ3 and the lower two-thirds of CZ4 in all three wells, indicating widespread lacustrine conditions to be present even in the late Serravallian (Fig. 2). Orbital driven processes (base level variation or erosion-denudation variation in the hinterland) almost certainly added to the complexity of the depositional system. Very high precipitation that characterized western Amazonia at least since the Early Miocene might have kept saline incursions out of the basin (most of the time) even though the system was at sea level and connected to sea. This configuration allowed for tidal regimes to act in western Amazonia (Räsänen *et al*., 1998; Gingras *et al*., 2002) without the widespread establishment of saline conditions (Wesselingh *et al.*, 2006b).

In summary, both internal and external driving mechanisms, including autocyclic, allocyclic and chaotic processes, shaped the Pebas system. The Pebas system can be characterized as a complex of lakes and wetlands with only limited marine influence. At the eastern margins it graded into the fluvial plains of rivers draining the craton areas. To the west, the Pebas system graded into the fluvial fringe of the emergent Andes. During recurring base level high stands on a range of time scales, interconnectivity of aquatic habitats was high, but the presence of meander belts and islands/swamps would have made the Pebas system a genuine mosaic lake/wetland system.

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Appendix

Mollusc species found in the well samples. ® indicates material that was probably reworked. MRM denotes mainly reworked molluscs.

Capahuari-Norte (1AB-3-204)	*Neritina etheridgei*	*Neritina ortoni*	*Neritina roxoi*	*Tryonia minuscula*	*Tryonia semituberculata*	*Tryonia scalarioides tuberculata*	*Tryonia s. scalarioides*	*Dyris ortoni*	*Dyris lintea*	*Dyris hauxwelli*	*Dyris tricarinatus*	*Dyris lataguensis*	*Dyris hoornae*	*Dyris elongatus*	*Dyris denticulatus*	*Onobops communis*	*Onobops ventricosus*	*Sioliella bella*	*Sioliella kadolskyi*	*Cochliopina?* *colombiana*	*Cochliopina?* sp. indet.	*Charadreon eucosmius*	*Sheppardiconcha tuberculifera*	*Sheppardiconcha coronata*	*Sheppardiconcha colombiana*	*Sheppardiconcha* cf. *bibliana*	Unionoidea sp. indet.	*Mytilopsis* sp. indet.	*Mytilopsis sallei*	*Pachydon obliquus*	*Pachydon carinatus*	*Pachydon erectus*	*Pachydon cebada*	*Pachydon hettneri*	Pachydontinae sp. indet.
2000-2250																																			
2300 top fossiliferous interval 2350																																			
2350																											x								
2400																																			
2450											cf																x								
2500																																			
2550																											x								x
2600																																			
2650																																			
2700				x				x	x		x		cf																						x
2750						x		x	x		x																			x					x
2800								cf	x																										x
2850									x		x																								
2900											cf													x						x					x
2950								x			x					cf														x		x			x
3000 LOD *S. tuberculifera* 3050																								x											
3050											x												x	x											x
3100	x	x		x				x			cf						x	?																	x
3150		x		x			x	x								x	x													x					x
3200				x				x	cf				cf			x	x										x	x		x					x

3250 LOD *C. eucosmius* 3300	x	x		x		x	x	cf							x								x	x	x					x
3300		x		x		x			cf						x				x	x						x				x
3350			x																											x
3400				x		x								cf	x					x										
3450		x				x	cf								cf	cf				x			x							x
3500	cf			x		x									x					x										
3550 top compacted zone 3600						cf																		x						
3600																				x										
3650									cf		cf												x							
3700						cf																	x							
3750 top ‘La Tagua’ taxa 3800						x	x		cf											cf		cf				x				
3800						x	x			x	cf®									x		cf	x							
3850					x	?	®			x	cf	®								x			x					cf	x	x
3900							x			x	cf							x					x							x
3950				®						cf	cf		cf				cf						x				x	cf	cf	x
4000						cf	x			x			x						x	cf										
4050							x			x			x						x	cf			x					x		x
4100					x					x			x							cf	x		x						x	
4150										x			cf						x				x							x
4200							x													cf			x					cf		x
4250																					x		x						cf	x
4300										x	cf				cf®														x	x
4350										x																				x
4400							x			x																				x
4450																							x						x	x
4500 top mrm 4550						?				x										cf			x							
4550																														
4600																														
4650										®												cf							®	
4700																			®			cf								
4750																														
4800																														
4850																			x				x							
4900																							x							
4950																							x							
5000																														

Appendix (cont.)

Huayuri-Sur	*Neritina etheridgei*	*Neritina ortoni*	*Tryonia minuscula*	*Tryonia semituberculata*	*Tryonia scalarioides tuberculata*	*Tryonia s. scalarioides*	*Dyris ortoni*	*Dyris lintea*	*Dyris tricarinatus*	*Dyris lataguensis*	*Dyris huberti*	*Dyris denticulatus*	*Onobops communis*	*Onobops ventricosus*	*Onobops? bisulcatus*	*Toxosoma globosum*	*Sioliella* sp.	*Tropidebora* s.l. sp.	*Cochliopina? convexa*	*Charadreon eucosmius*	*Sheppardiconcha tuberculifera*	*Sheppardiconcha colombiana*	*Sheppardiconcha lataguensis*	*Sheppardiconcha bibliana*	Unionoidea sp. indet.	*Mytilopsis* sp. indet.	*Mytilopsis sallei*	*Pachydon obliquus*	*Pachydon amazonensis*	*Pachydon telliniformis*	*Pachydon tenuis*	*Pachydon cebada*	*Pachydon trigonalis*	*Pachydon hettneri*	Pachydontinae sp. indet.
2010 LOD *S. tuberculifera* 2050											cf																								x
2050			cf																		x							x	cf						x
2100	cf												cf					x										x							x
2150			x				x						x	x				x			x							x					x		x
2200		x	x		x		x						cf		cf			x			x							x							x
2250		x		x	cf		x						cf	cf							x							x							x
2300				x	cf	x	x		x					x			x				cf					x		x							
2350		x	x	x			x		x					cf				x			x				x			x		cf					
2400 LOD *C. eucosmius* 2450		x		x	x		x							cf							x				x	x		x							x
2450		cf			x															x	x							x					?		
2500	cf	cf	x	x	x		cf						cf	cf		x					cf				x			x							x
2550			x											x						x	cf				x										x
2600		x					x						cf	cf						x	x				x			x							x
2650			x				x		cf				?	cf		cf				x	cf				x	x		x							x
2700				x			cf														x			cf				cf							x
2750			x				x						?		x										x			x			x				x
2800 top compacted zone 2850														x						x	x			cf	x			®?							x
2850		®					x	®						x						x	x			cf	x										x
2900							x	x	x											x	cf			cf	x		x	®							
2950 top 'La Tagua' taxa 3000							x	x	cf					cf							x				x										x
3000			®				cf	x				x								x	cf			cf	x										x
3050				x			cf	x		x		x							x		x			cf	x			®						cf	
3100			®				cf	x		x		x									x	cf			x									cf	®

3150	x	x	x	x			cf							x
3200	®	x	x	x			x		cf	x				
3250	®	x	cf	x			cf		cf	x				x
3300		x	x	x		x	cf			x		cf		®
3350		x		x			cf	cf				cf		x
3400	x	x	x		®	x	cf		cf	x			x	®
3450		x	x	x			x			x				®
3500	cf	x		cf	®						®		x	®
3550		x	x	cf			cf			x			cf	®
3600		x	x	x		x	cf		cf	x		cf		®
3650	®	x	x	cf			cf		x		®			®
3700	®	x	x	cf			cf		cf				®	®
3750	®	x						x						®
3800 top mrm 3850	®	x					®		x	x				®
3850														
3900														
3950														
4000-5050 base														

Appendix (cont.)

Jibaro-7 (1AB-21-181)

	Neritina roxoi	*Neritina ortoni*	*Neritina etheridgei*	*Feliconcha reticulata*	*Tryonia minuscula*	*Tryonia semituberculata*	*Tryonia s. tuberculata*	*Tryonia s. scalarioides*	*Dyris ortoni*	*Dyris hauxwelli*	*Dyris lintea*	*Dyris tricarinatus*	*Dyris lataguensis*	*Dyris elongatus*	*Dyris hoornae*	*Dyris mattii*	*Dyris huberti*	*Dyris denticulatus*	*Onobops communis*	*Onobops ventricosus*	*Onobops? iquitensis*	*Onobops? bisulcatus*	*Toxosoma globosum*	*Tropidobora s.l.* sp.	*Cochliopina?* sp. indet.	*Charadreon eucosmius*	*Sheppardiconcha tuberculifera*	*Sheppardiconcha coronata*	*Sheppardiconcha septencincta*	*Sheppardiconcha lataguensis*	*Sheppardiconcha bibliana*	Unionoidea sp. indet.	*Mytilopsis* sp. indet.	*Pachydon obliquus*	*Pachydon erectus*	*Pachydon elongatus*	*Pachydon telliniformis*	*Pachydon tenuis*	*Pachydon maaikeae*	*Pachydon cebada*	*Pachydon trigonalis*	*Pachydon hettneri*	*Exallocorbula dispar*	Pachydontinae sp. indet.
1000 top fossiliferous interval 1050																																												
1050					x			cf	?																				cf															
1100																													cf			x												
1150					x										x				x																									x
1200					x				x		cf				x	cf	cf											cf																x
1250					x			x	cf					x		x	x											cf				x	x	x										
1300					cf			x			x			x	x		cf											cf					x											x
1350									x		x				x																													x
1400					x				x		x			x	cf																													
1450								x			x									x																								
1500					x				x		x	x				cf																												
1550					x				x		x	x					cf			x														x										
1600					x			x	x		x																						x	x			x							x
1650									x		x																																	
1700					cf				x																									x										
1750					x				x		x	x																									cf							x
1800											x						x		x														x											x
1850										cf										x				x										x							x			x
1900 LOD *S. tuberculifera* 1950					x				x		x	x																						x							x			x
1950				x	x	cf			x		x	x							cf		x						x							x			x							x
2000					x		x		x			x															x							x									cf	x
2050					x		x		x		x	x								x			cf				x							x	x						cf			x

2100				x	cf		x	x									x					x		cf						x
2150 LOD *C. eucosmius* 2200		x		x			x	x	cf													x								x
2200		cf						x	x			x				x						x	x							x
2250			cf	x		x	x		x				x	cf			x					x			x				x	x
2300								x	x							x	x			x	x	x			x					x
2350		cf					cf	x	x							x	x					x			cf				x	x
2400							x		x				cf				x			x										x
2450	x				cf		x		x				cf			x	x					x	x			x				x
2500			cf	x	x		x		x				cf			x	x			x		x	x							x
2550					cf		x		x				x			x	x			x										x
2600							x	x					x			x	x			x	x	cf				x				x
2650 top 'La Tagua' taxa 2900					cf		x	x	x				x			x	x			x	x	x								x
2700 top compacted zone 2750							x	x			x					x	x			x		®?								®
2750								x				cf			x	x	x		cf	x		x								
2800							x	x								x	x		x	x										
2850						®	x	x									x		x	x										
2900							x	x		x	x					x	x			x										x
2950										x	x					cf			x	x							cf	x		x
3000								x		x	cf						x		cf	x										
3050								x			x					x	x			x										
3100							®	x		x	x						x	cf												
3150											x					cf			x	x										®
3200								x		x							x			x										
3250										x										x										
3300																														®
3350 top mrm 3400								x									®			x										®
3400																														
3450-5050 base																														